EXTERNAL DATA EXCHANGE ISSUES FOR STATE ESTIMATION IN POWER SYSTEMS

By

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Abstract

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Nowadays, large interconnections comprise several reliability coordinators and many balancing authorities. Each reliability coordinator and balancing authority has its own control center with its own state estimator for monitoring the area under its control. The portion of the network outside a utility's control area is known as the external network and the modeling of the external system is required for a state estimator monitoring an internal system. In reality, each of these reliability coordinators has a unique external model which causes the largest errors in the real time models for maintaining situation awareness.

In recent years, there has been a renewed interest in the situation awareness for the entire interconnection as a result of recent cascading blackouts which affected an area not covered by any one control center. The feasibility of multi-area power system state estimation has already been studied from an algorithmic viewpoint and most of these studies have been in the investigation of state estimation schemes involving independent state estimators for each control area and a central coordinator.

The actual implementation of a state estimator, however, depends on various factors, such as the time skew of data, the accuracy of the network database, the availability of raw data versus state-estimated data, and sensitive issues regarding the proprietary nature of the data. These issues are studied in this dissertation to determine the data exchange requirements for minimizing the errors in state estimation

Specifically, the effects of various levels of data exchange between the external model and the state estimator on state estimation accuracy are studied. This includes investigating the retention of more detailed external models than the present day practice of only retaining equivalents at the boundary buses. The differences between exchanging SCADA data versus state estimated data are also investigated and the importance of correct topology knowledge during state estimation is investigated. Finally, the effects of data exchange during state estimation on ensuing contingency analysis accuracy are also studied. All the studies are performed on two test bed systems. The first one is the IEEE-118 bus system and the second one is the 1648 bus system.

Keywords: External Model, Multi-area state estimation, Energy Management System.

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1. INTRODUCTION

1.1. Motivation

Power system state estimation is the process in which a best estimate of the state of the system is obtained based on a set of real-time system measurements for a pre-determined system model [1]. State estimation was first introduced by Fred Schweppe in 1970 [2]-[4], and the introduction of the state estimation function provided SCADA system computers with more capabilities, and also led to the establishment of Energy Management Systems (EMS) [5]. The power system state estimator represents a core part of modern EMS since it helps provide a real-time model of the system from a snapshot of measurements, which is critical to other functions of the EMS, including contingency analysis, security constrained dispatch, automatic voltage control and economic dispatch controls.

Nowadays, large interconnections may comprise several reliability coordinators and hundreds of balancing authorities. Each reliability coordinator and balancing authority has its own control center with its own state estimator for monitoring the area under its jurisdiction. The portion of the network which is outside each utility's control area is known as the external network [6]. The modeling of the external system is required for a state estimator monitoring an internal system. In reality, each of these reliability coordinators has a unique external model which causes the largest errors in the real time models for maintaining situation awareness.

In August 2003, a cascading blackout occurred, affecting a large area covering more than one control area, leading to a renewed interest in situation awareness for the entire interconnection. In fact, it is recommended in a DOE/FERC report that the monitoring of the entire North American grid be performed by a monitoring center covering the entire interconnection [7]. It is cited in this report that these system wide control centers would be feasible with sufficient phasor measurement units (PMUs) installed into the power system. However, the number of PMUs in the current power system is obviously insufficient for the operation of such a control center.

The feasibility of performing state estimation on multi-area or interconnected power systems has been studied from an algorithmic-solution viewpoint in the literature.

Most of the studies have been in the investigation of a state estimation scheme involving independent state estimators for each area and a central coordinator [8]-[17]. In [8], the individual areas of the power system are first solved for and then the boundary buses form an interconnection area which is solved at a central level. The goal of solving this multi-area state estimation in two levels is to reduce the amount of memory requirements and computation time.

In [9], the individual areas of the power system are first solved for by conventional state estimation methods and then, these solutions are coordinated to obtain the state estimation solution for the entire power system. The coordination is done starting with the neighboring systems of the system with the slack bus, and is extended at each step to further neighboring students until all sub-areas are coordinated. The benefit of this method lies in its speed and flexibility in obtaining a state estimation solution.

In [10], the areas in the power system are decomposed into overlapping areas where the boundary buses extended outside each area into the neighboring areas. The conventional state estimation method is performed by each area and the estimates of the boundary states of all areas are sent to a central coordinator, which then solves for the states at these boundary buses again, and the overall system solution can then be obtained. This method also allows for the inclusion of synchronized phasor measurements in the measurement sets for state estimation. The main advantages of this method are that very little data exchange has to be performed between various areas of the power system, although the central coordinator will have access to area state estimation solutions.

An optimization approach to multi-area power system state estimation is proposed in [11]. This method allows for estimating for the state of a multiarea power system while preserving the independence of each area, and the need for a central coordinator is eliminated when this method is used. This technique relies on directly solving pertinent single area optimization problems, and individual areas only need to exchange order information during the optimization process.

Another Two-level State Estimation algorithm is proposed in [12], and this method is similar to that in [10] in that overlapping areas are first solved individually. The difference in this algorithm lies in that pseudo measurements are created at boundary buses through modification of the boundary bus injections to account for lines connected to the boundary bus. Hence, only the modified boundary bus injection measurements need to be provided to the central coordinator for the coordination phase.

In [13], a multi-area power system state estimation algorithm is proposed, where the multi-area power system is decomposed into non-overlapping areas and state estimation is solved for all these areas. In previously proposed algorithms, the coordination phase was performed such that the boundary buses were solved for once more to ensure the accuracy of the state estimation results. In this algorithm, sensitive internal buses, which are defined as internal buses of subsystems whose sensitivity indices to the boundary buses of the same subsystem are sufficiently high, are also included in the coordination, or aggregation phase. It is shown in the paper that there are cases where neglecting the sensitive internal buses during coordination may lead to less accurate state estimation results. Two surveys with more extensive detail on other multi-area state estimation methods are always available [18]-[19].

Some issues regarding the state estimation algorithms proposed in the literature are now discussed. First of all, it is worth noting that most of these algorithms, especially the older ones, are aimed at reducing the size of the state estimation problem so that the computation time can be reduced. With the advance of technology, computation power is becoming less of an issue, and hence, there is renewed interest in studying the effects of solving for a larger area of the power system. Secondly, in most of the algorithms, the goal is to allow state estimation to be performed with minimal data exchange with neighboring areas, since this has been the trend in industry. There is little incentive in understanding the effects of additional knowledge of neighboring systems on state estimation accuracy.

The actual implementation of a state estimator, however, depends on many other factors, such as the time skew of the data that basically unsynchronizes the data in the state estimation process, the accuracy of the network database, the availability of raw data versus state-estimated data, and sensitive issues regarding the proprietary nature of the data. These issues are all related to data exchange between various control centers in power systems.

In this dissertation, the effects of data exchange with the external system on internal state estimation accuracy are investigated. This includes the investigation of having more detailed external models as compared with the current practice of equivalencing to the boundary buses.

1.2. Objective and Findings

In this dissertation, a set of studies is performed to investigate various effects of data exchange with the external system on state estimation accuracy. This includes studying how different levels and amounts of data exchange with the external system affect the accuracy of the internal state estimator. Studies are also performed to compare the effects of exchanging different types of data, namely, SCADA data and state estimated data. The effects of having incorrect topology knowledge of the external model during data exchange as a result of topology processor errors of neighboring control centers will also be studied. As aforementioned, the goal of state estimation is to provide an accurate real-time model of the system operating conditions, which can be used as an input for other EMS functions such as contingency analysis. Therefore, the effects of data exchange during state estimation on the accuracy of ensuing contingency analysis are also studied in this dissertation.

Most of the testing performed in this dissertation will be done on the IEEE-118 bus system. The system is configured in a way to represent a power system with several control centers, setting up the foundation for investigating the effects of data exchange with the external system. A 1648 bus system is also used in some of the testing in this dissertation to observe whether findings on the IEEE-118 bus system can be extended to larger systems.

1.3. Outline

This dissertation comprises 6 chapters and is outlined as follows. The motivation behind the research in this dissertation, together with the objectives and findings are described in Chapter 1.

A short review of power system state estimation and various methods of external modeling of power systems are included in Chapter 2. The general approach to be adopted for the study of the effects of data exchange with the external system on state estimation accuracy will also be described. As aforementioned, the IEEE-118 bus system is one of the testbed systems for the research work in this dissertation, and the configuration of this system will be illustrated as well.

In Chapter 3, the effects of exchanging different amounts of SCADA data on internal system accuracy are studied. Studies in this chapter focus on observing the effects of data exchange with only certain portions of the external system. Various scenarios are created for these studies and the investigation is conducted on both the IEEE-118 bus system and the 1648 bus system.

The effects of exchanging SCADA data and state estimated data are compared in Chapter 4. The effects of errors in the topology processor of the external system during data exchange on internal state estimation will also be considered. These studies will first be studied on the IEEE-118 bus system, while the effects of topology errors during state estimation will also be studied on the 1648 bus system.

Chapter 5 illustrates the effects of solving the state estimator with retention of different amounts of the external model. An algorithm is proposed for determining the proximity of topology errors in the external system and is tested on the IEEE-118 bus system. The effects of data exchange during state estimation on ensuing contingency analysis are also studied on both the IEEE-118 bus system and the 1648 bus system.

A summary of the findings in this dissertation will be provided in Chapter 6.

2. Multi-Area Power System State Estimation

2.1. Introduction

The state estimator accesses measurements from monitored areas of the control center to determine the best estimate of the state of the power system based on these redundant measurements [1]. The state of the power system refers to voltage magnitude and angle at every bus of the control area, since other attributes of the power system, such as the real and reactive power injections at each bus can be calculated from the state variables.

In this chapter, the traditional state estimation algorithm will be described briefly, and a review of external modeling methods is provided. Then, the approach adopted to investigate the effects of different levels and types of data exchange on state estimation accuracy will be described.

2.2. State Estimation

State estimation refers to the process in which the bus voltage magnitude and angles at all system buses are obtained at a given point of time. Theoretically, this could be achieved by having very accurate synchronized phasor measurements at all buses in the system, from which the voltage phasors at each bus could be obtained. Practically, this is not possible yet since the number of PMUs populated into real power systems is insignificant compared to the number of buses in the power system. Moreover, such an approach is vulnerable to measurement errors or telemetry errors.

State estimation is therefore performed by obtaining a set of redundant measurements to filter out measurement errors to find an optimal estimate.

Conventionally, some commonly used measurements in power system state estimation include:

- Voltage magnitude measurements at buses
- Real and reactive power injections at buses
- Real and reactive power flows on branches

With an increasing number of PMUs being populated into power systems, synchronized voltage phasor measurements can be used as well. The goal of state estimation is to determine a best estimate of the state of the system based on the measurements that are obtained from the system.

The most commonly adopted method to achieve this goal is through maximum likelihood estimation (MLE).

Consider a joint probability density function (p.d.f) representing the probability of measuring n independent measurements with the same Gaussian p.d.f.. The joint p.d.f. can then be expressed as the product of the individual p.d.f.s as it is assumed that the measurements are all Gaussian and independent.

The likelihood function $f_n(z)$ can be represented as

$$f_n(z) = f(z_1)f(z_2)\cdots f(z_n) \qquad (2\text{-}1)$$

where z_i represents the i^{th} measurement and n is the total number of measurements.

$f(z_i) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}\left\{\frac{z_i-\mu}{\sigma}\right\}^2}$ is the probability density function for a Gaussian random variable z_i.

The objective of MLE is to maximize the likelihood function by varying the assumed functions of the density function, which are the mean μ_i and standard deviation σ_i respectively in this case. The Log-Likelihood function is often used to replace the likelihood function to simplify the process, and is denoted as:

$$\mathcal{L} = \log f_n(z) = \sum_{i=1}^{n} \log f(z_i) \qquad (2\text{-}2)$$

Since the measurements are assumed to have Gaussian distribution, the above equation further simplifies to become:

$$\mathcal{L} = \log f_n(z) = \sum_{i=1}^{n} \log f(z_i) = -\frac{1}{2}\sum_{i=1}^{n}\left(\frac{z_i-\mu_i}{\sigma_i}\right)^2 - \frac{n}{2}\log 2\pi - \sum_{i=1}^{n}\log \sigma_i \qquad (2\text{-}3)$$

MLE maximizes the Log-Likelihood function $\mathcal{L}$ for a given set of n observations z_1 , …, z_n . Note that maximizing $\mathcal{L} = \log f_n(z)$ is the same as minimizing $\frac{1}{2}\sum_{i=1}^{n}\left(\frac{z_i-\mu_i}{\sigma_i}\right)^2$.

The minimization problem can then be expressed as

$$\min \sum_{i=1}^{n} W_{ii} e_i^2 \qquad (2\text{-}4)$$

subject to $z_i = h_i(\boldsymbol{x}) + e_i$ for i=1, … , n

where z_i is the i^{th} measurement

$h_i(\boldsymbol{x})$ is a nonlinear function relating the system state vector $\boldsymbol{x}$ to the i^{th} measurement

$e_i = z_i - \mu_i = z_i - E(z_i)$ is the error of measurement z_i

$W_{ii} = \frac{1}{\sigma_i^2}$ is the weight for measurement error e_i and is used to represent the accuracy of measurement z_i

The solution of the above optimization problem is known as the weighted least squares (WLS) estimator for $\boldsymbol{x}$. Certain assumptions are made regarding the measurement errors, and they are listed below:

- $E(e_i) = 0\,, i = 1, \dots, n$ (Measurement errors have a mean value of zero)
- $E\left[e_i e_j\right] = 0$ for $i \neq j$ (Measurement errors are independent)

Hence, $Cov(e) = E[e \cdot e^T] = \boldsymbol{R} = diag\{\sigma_1^2, \sigma_2^2, \dots, \sigma_m^2\}$

The minimization problem can be expressed as

$$S(\boldsymbol{x}) = \sum_{i=1}^{k} \frac{\left(z_i - h_i(x)\right)^2}{R_{ii}} \qquad (2\text{-}5)$$

where R_{ii} is the i^{th} diagonal entry of the covariance matrix $\boldsymbol{R}$ and is related to the standard deviation σ_i of measurement i to reflect the expected accuracy of the corresponding meter providing the measurement.

The first-order optimality conditions for the minimizing problem can be represented as

$$g(\boldsymbol{x}) = \frac{\partial S(x)}{\partial x} = -\boldsymbol{H}^{\boldsymbol{T}}(\boldsymbol{x})\boldsymbol{R}^{-1}[\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x})] = 0 \qquad (2\text{-}6)$$

where $\boldsymbol{H}(\boldsymbol{x}) = \left[\frac{\partial h(x)}{\partial x}\right]$

$\boldsymbol{z} = [z_1, z_2, \dots, z_k]$ is the measurement vector

$\boldsymbol{h}(\boldsymbol{x}) = [h_1(\boldsymbol{x}), h_2(\boldsymbol{x}), \dots, h_n(\boldsymbol{x})]$ is the measurement function vector

Expanding $g(\boldsymbol{x})$ into its Taylor series around the state vector x^k gives

$$g(\boldsymbol{x}) = g(\boldsymbol{x}^k) + G(\boldsymbol{x}^k)(\boldsymbol{x} - \boldsymbol{x}^k) + h.o.t = 0 \qquad (2\text{-}7)$$

where $\boldsymbol{G}(\boldsymbol{x}^k) = \left[\frac{\partial g(x^k)}{\partial x}\right] = \boldsymbol{H^T}(\boldsymbol{x}^k)\boldsymbol{R}^{-1}\boldsymbol{H^T}(\boldsymbol{x}^k)$ and is known as the gain matrix

By neglecting the higher order terms (h.o.t.) in the equation above, and using Newton's method, the iteration solution scheme for $\boldsymbol{x^k}$ can be found to be:

$$\boldsymbol{x}^{k+1} = \boldsymbol{x}^k - [\boldsymbol{G}(\boldsymbol{x}^k)]^{-1}\boldsymbol{g}(\boldsymbol{x}^k) \qquad (2\text{-}8)$$

where *k* is the iteration index

$\boldsymbol{x}^k$ is the solution vector at iteration *k*

Note that the gain matrix $\boldsymbol{G}(\boldsymbol{x})$ is sparse, positive definite and symmetric if the system is fully observable, and hence can be inverted whenever the system is observable. In practice, the gain matrix $\boldsymbol{G}(\boldsymbol{x})$ is not inverted, but is decomposed into triangular factors so that the following form of equation 2-9 below can be solved using forward and backward substitutions at each iteration *k*.

$$[\boldsymbol{G}(\boldsymbol{x}^k)](\boldsymbol{x}^{k+1} - \boldsymbol{x}^k) = \boldsymbol{H}^T(\boldsymbol{x}^k)\boldsymbol{R}^{-1}[\boldsymbol{z} - \boldsymbol{h}(\boldsymbol{x}^k)] \qquad (2\text{-}9)$$

The means to which state estimation is performed has been discussed above, and since the focus of this dissertation is on the effects of data exchange on internal state estimation accuracy rather than on the state estimation algorithm itself, other topics including bad data detection and observability analysis are not discussed in this dissertation.

2.3. External Network Modeling

Consider an interconnected system as shown in Figure 1 below. The system under study is defined as the internal system, while all its neighboring systems are denoted as the external system. The buses with direct contact to the external system are defined as internal boundary buses.

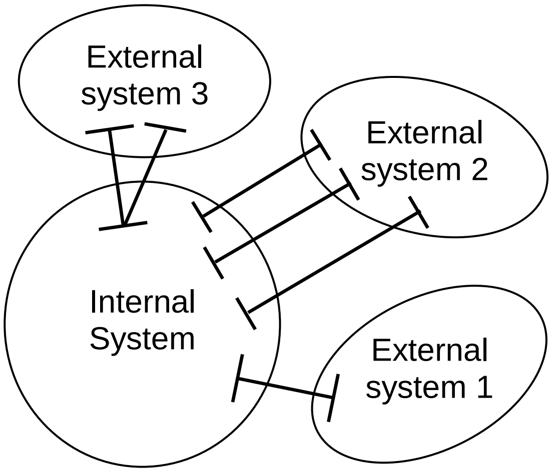

Figure 1. Schematics of an interconnected system

In any multi-area interconnected power system, each system has real-time access to its own measurements and topology, while real-time access to external topology and measurements are determined by the amount of data exchanged with the neighbors.

The modeling of the external network is significant to various EMS functions which are dependent on the accuracy of the external model [6]. Such EMS functions include contingency analysis, automatic generation control, optimal power flow, and economic dispatch functions.

Usually, each area represents its own network in detail but uses a static network equivalent for the representation of its neighbors [20]. These equivalent external networks can range from representing the detailed model of the near neighbors to eliminating all the external nodes right up to the boundary buses. The equivalent model remains accurate as long as the external operating conditions remain close to those of the base case. The base case refers to the operating conditions of the power system when the equivalent model was constructed. The impacts of changes in external network topology and/or operating conditions on the results of the internal state estimation and subsequent contingency analysis are studied in [21], where it is shown that having access to a limited number of PMUs in the external network may significantly reduce errors.

The problem of external network modeling is well investigated by many researchers in the past decades [6],[22]-[53]. There are two main approaches for modeling the external network, and they will be introduced in this section.

The first approach involves developing an equivalent for the external network, which is therefore represented as a low order model reduced to or near the internal system's boundary buses and is then updated in real time.

The second approach is the external solution method, where the external network is retained and represented in detail and is then solved in real time by different techniques.

2.3.1. External equivalent methods

The approach for creating external equivalents is as follows. First, a reduction of the external network is performed off-line based on normal or base case operating conditions. More than one equivalent can be created to represent different system operating conditions, such as different loading levels and they can be selected depending on the real-time system conditions.

There are two common methods for creating equivalents and they are known as the Ward Type Equivalents and the REI Type equivalents. For the Ward Type equivalent, the internal, boundary and external bus equations are rewritten in a block format and the external buses are eliminated and the equivalent transmission lines between the boundary buses can be calculated and are represented in the new reduced admittance matrix. There are several variations of the Ward Type equivalent, where the main difference is in the treatment of the equivalent injections at the boundary buses [26]-[34]. The simplest and most common variation is the passive Ward, where the injections are ignored, such that the resulting equivalent is just a representation of the branches of the original external network, but not of the loads or generation. The definition of the boundary buses and external buses provides the flexibility of retaining larger amounts of the external system.

For the REI Type equivalent, the generator and load buses of the external network are reduced separately [35]. As in the case for Ward Type equivalents, there are several variations of the REI equivalent and there is some flexibility in deciding whether it is desired to retain more buses for the equivalent [36]-[41].

Regardless of the type of equivalent constructed, this equivalent is attached to the boundary of the internal system after the internal network is solved for. As the bus voltages at the boundary buses are known from the internal state estimator, the injections at these boundary buses can then be calculated. Large mismatches may occur at these boundary buses, since the attached equivalents are created for base case conditions, which may be totally different from the actual real time operating conditions.

The equivalents are then updated to match the real time operating conditions. One of the simplest and most common ways in which this can be done is by using the boundary mismatches as the new boundary injections. This method is convenient since only the boundary injections are updated, and the equivalent itself is not modified. Obviously, errors may be quite high in ensuing EMS functions when this method is used.

The passive Ward equivalent with boundary matching injections is the most commonly adopted method because the simplicity of implementation. This method fares decently in most cases where there are no topology changes from the base case, where the equivalent is created.

The main advantage of using external equivalents is that the size of the external model is reduced and does not assume the availability of a large amount of real time data. However, this may not necessarily provide great advantages in computation, since the connections of the equivalent with all the boundary buses lead to a loss of sparsity in the reduced admittance matrix for the rows and columns relating to the boundary buses. Another issue is that these equivalents are by nature approximations, and suffer from the introduction of errors even for the best equivalent techniques [23]-[25]. Moreover, external equivalents do not allow or provide the flexibility to make use of any external system data which is available to a control center.

2.3.2. External solution methods

For the external solution methods, the external system is represented in detail, and hence, the first step is to assume the real time data for the external system [42].

This data includes the generation, loading and topology of the external system. Obviously, the more real time data that can be obtained regarding the external system, the more accurate this external model would be. The key consideration is the procedure to be taken when such real time data cannot be obtained. In such a situation, the best assumption that can be made is that the system is operating in a situation close to the base case condition. The assumptions include considering the topology in the external system to be the same as that during the base case, meaning that all circuit breakers are normal and all equipment is operational. It is also assumed that the voltages at all external buses are controlled within the expected limits. The loading for the external system is assumed to be proportional to the load level of the internal system. The proportional constant for this assumption is based on historical data of the system.

Obviously, any real-time knowledge or data of the external system which is obtained will be assumed to be correct and would be used in place of the assumptions. For example, in the event that it is already known that a topology change in the external system has occurred, there is no reason to continue assuming the base case topology for the external system.

It is inherent that sufficient data is available to ensure that the entire system is observable. In situations where there is insufficient real-time data of the external system, pseudo measurements based on the data assumptions are created to keep the external network observable.

With the above mentioned procedure for assuming the real time data for the external model, the network solution can be calculated. There are two main approaches for obtaining the network solutions. The first is the power flow solution, where both the Newton-Raphson and the Fast Decoupled Algorithms can be used [43]-[47]. The state estimation solution for the internal system is first obtained, and then, a power flow solution is used to solve for the complex voltages at all external buses. The boundary buses are treated as swing buses so that the voltage and angle at these buses can be kept at the values obtained from internal state estimation solution. As the boundary buses have all been defined as slack buses, all modeling or parameter errors would show up at these boundary buses in the power flow solution. In a large power system, there is usually a larger number of buses in the external model compared to the number of boundary buses. Since the errors are all lumped at the boundary buses, it becomes difficult to locate the area of the external system where the errors are.

In another approach, the state estimation solution is used to obtain the solution for the external network [48]-[53]. This approach can be further classified into the one-pass state estimation method and the two-pass state estimation method. In the one-pass method, a single state estimation run is performed for the entire network [49]-[51]. Power flow variables such as voltages and line flows are treated as pseudo measurements. In the event that real-time data of the external system can be obtained, these will be used instead. To solve the state estimation for the entire network, the measurement set comprises real-time measurements from the internal system, while a combination of real-time measurements and pseudo measurements depending on the amount of data exchanged performed with the external system.

In the two-pass method, state estimation is first run on the internal system to produce an initial estimate of the internal system state [52]-[53]. The state estimation solution for the external network is then solved. The external network to be solved is extended up to the boundary buses of the internal system. The measurement set for the external network includes a combination of real-time measurements and pseudo measurements based on base case data of the external network. The external solution and internal solution boundary buses are given injections and line flows which are calculated from the internal system's state estimation solution. These are considered as high confidence measurements since the boundary conditions should match at the boundary for the internal network solution and the external network solution.

2.4. Approach

It was discussed in the previous section that external equivalents may lead to large errors in state estimation when there are changes in the external system's operating conditions, and hence, the detailed external model will be used in this dissertation for the investigation of the effects of data exchange on state estimation accuracy.

The current practice for inter-utility real-time data exchange in North America involves the Inter-Control Center Communications Protocol (ICCP). While ICCP provides access to a pool of real-time measurements from neighboring companies, these measurements are taken from the real system and have to be mapped to the external equivalent. When the external equivalent is small, the number of external measurements exchanged is small compared to all the measurements in the external system.

Since the detailed external model will be used in this dissertation, the neighboring areas of the internal system for all test systems will be kept intact and will not be equivalenced. Either real-time data from data exchange or pseudo measurements will be used to ensure observability of the entire system.

The general approach in which studies will be carried out to investigate the effects of different levels and types of data exchange on internal state estimation accuracy is as follows.

1. A base case is created, and its power flow solution is saved and denoted as PF^{B}.
2. Additional cases are created to represent the power system under different operating conditions, which would lead to different power flow solutions. This is primarily done through either topology changes in the system or generation shifts. The power flow solution for each of these additional cases is denoted by PF^{k}, where k is the case number.
3. It is assumed that conventional measurements such as voltage magnitudes, real and reactive power injections and line flows are available to the state estimator. Measurements are created by incorporating small random errors to the values obtained in the power flow solutions. There random errors are assumed to have a Gaussian distribution with zero mean and standard deviation of 0.01 on per unit measurements. The measurement set created

from PF^B is denoted as M^B and the measurements sets created from PF^k are denoted as M^K, where $1 \leq k \leq n$, where n is the total number of cases.

4. State estimation is performed for each case. It is assumed that measurements in the internal system are always up to date, i.e., measurements for the internal system are always taken from M^k for case k. The measurements to be used for the external system are dependent on the type and amount of data specified in each scenario. The various scenarios created to represent different types and levels of data exchanged will be described in corresponding chapters and sections of this dissertation.

It is important to have a basis to measure the effect of data exchange on the accuracy of state estimators. A detailed study on the proposal of various metrics for commercial state estimators can be found in the literature [54]. The following metric is one of those that is selected to be used in investigations involving the effects of different levels of data exchange on internal state estimation and is illustrated in the following equation.

$$J_{118} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^*\right] \qquad \text{(2-10)}$$

where $\vec{V_i}$ is the estimated complex voltage at bus i

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus i based on the power flow solution

N is the number of internal system buses

The above metric takes the difference between the state estimated complex voltage and the exact complex voltage at each internal bus of the system, and multiples this value by its complete conjugate so that index J_{118} becomes a real number and acts as an index of internal state estimation accuracy. N represents the number of buses in the internal system only, since only the buses within one's own control area are of interest.

Obviously, a smaller value of J_{118} indicates a higher level of accuracy for the internal state estimator. It is worth noting that while the above metric provides a general idea on the accuracy of internal state estimation, there is the possibility that the metric can be misleading in the event that there is a sufficiently large error at a single bus, which would lead to the apparent observation of a large error in the entire internal system. On the other hand, it is also possible that a single error at a boundary bus might be hidden by just observing the metric if the number of internal system buses is large enough. Intuitively, it is expected that errors in internal state estimation would be more pronounced at the boundary buses, and so, the errors at the boundary buses are also checked for each scenario. The error at each bus is calculated through the following equation which essentially just calculates the absolute value of the difference between the estimated complex voltage and the exact complex voltage at the specified bus:

$$Error_i = \left| \overrightarrow{V_i} - \overrightarrow{V_i^{pf}} \right| \tag{2-11}$$

where $\overrightarrow{V_i}$ is the estimated complex voltage at bus *i*

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the power flow solution

Throughout this dissertation, the errors at boundary buses are noted for all studies, and will be illustrated in cases where deemed necessary in order to provide greater insight to understanding the effects of data exchange on internal state estimation accuracy.

2.5. Test bed for experiments on data exchange

The IEEE-118 bus system is adopted as the test bed system for simulations to investigate the effects of various levels and types of data exchange on the accuracy of internal state estimation. This system is widely adopted in various types of studies in power system analysis research, and helps in noticing trends in the effects of data exchange, so that further and more specific studies can be performed on a larger test bed system. As aforementioned, the detailed external model will be adopted for studying the effects of different levels of data exchange.

A larger power system is also used for further studies on some trends discovered from the IEEE-118 bus system. The large system to be used is the 1648 bus system, which is a benchmark system provided in the commercial power analysis software PSSE by PTI technologies.

2.6. Preliminary study of levels of data exchange

Preliminary studies are carried out on the IEEE-118 bus system to gain some insight on the general effects of data exchange on internal state estimation accuracy in the event of changes in system operating conditions. Figure 2 illustrates the IEEE-118 bus system with area I denoted as the internal system, while the rest of the system is the external system.

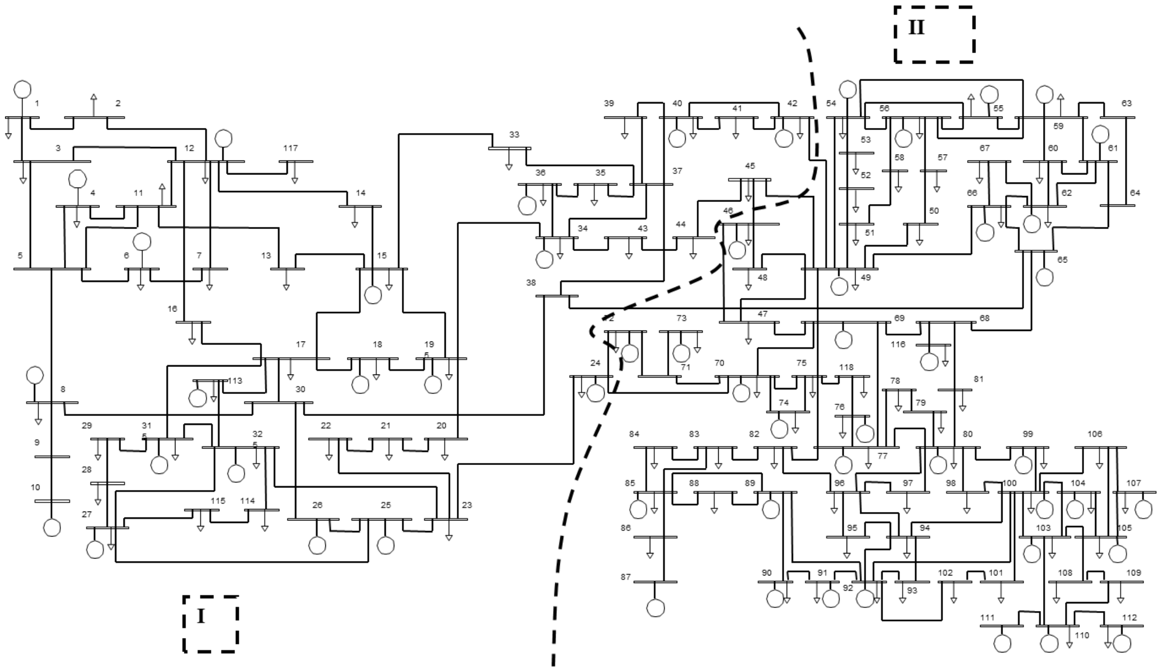

Figure 2. IEEE-118 bus test bed system

A list of cases is created where there is a single topology change (line outage) in the external system for each case, and simulations are run for different levels of data exchange corresponding to each scenario. The scenarios representing various levels of SCADA data exchanged are summarized in TABLE I. It is not practical to list the values of the state estimation accuracy metric for each case, so the mean value of this metric for all the cases (denoted J_{118} (Mean)) is illustrated.

TABLE I. Study of effects of different levels of data exchange on state estimation accuracy (Testbed system: IEEE-118 bus system in Figure 2)

Scenario	Data exchanged with external system	J_{118} (Mean)
2A	• No data exchange. • Pseudo measurements are created for buses in the external system to ensure system remains observable	2.19x10^{-1}
2B	• Real and reactive power injection measurements at each bus in the external system • Topology data of the external system	6.3x10^{-5}
2C	• Voltage magnitude, real and reactive power injection and flow measurements in the external system • Topology data of the external system	5.0x10^{-5}

As expected, the errors tend to be large when there is no data exchange. This is because the pseudo measurements created to ensure the observability of the external system are based on the base case operating conditions. In the event that topology changes are incurred in the external system, the operating conditions may shift and deviate from those of the base case, and hence, these pseudo measurements fail to reflect the actual operating conditions of the external system.

It is noted that having some level of data exchange with the external system suffices to enhance the accuracy of internal state estimation greatly, especially in cases where the topology change causes larger changes in the system operating conditions. It can be observed that there is little difference in the level of accuracy of state estimation for Scenarios 2B and 2C, since the data exchanged in scenario 2B is already sufficient for very accurate internal state estimation results. These preliminary results illustrate that data exchange helps improve internal state estimation and helps provide the platform for further investigation in ensuing sections of the report. It is also worth noting that having an excessive amount of data does not necessarily improve state estimation accuracy once the data exchanged is sufficient to guarantee a high level of accuracy.

2.7. Summary

In this chapter, a review of power system state estimation using the WLS algorithm and various methods in which the external model for interconnected power systems is created has been provided. The approach in which studies in this dissertation will be conducted to study the effects of data exchange with the external system on state estimation accuracy is described in detail. Finally, some preliminary results on the IEEE-118 bus testbed are shown to show the importance of data exchange in ensuring accurate state estimation results.

3. EFFECTS OF EXCHANGE OF DIFFERENT AMOUNTS OF DATA ON INTERNAL STATE ESTIMATION

3.1. Introduction

In the previous chapter, preliminary studies helped to illustrate the need for data exchange to help improve internal state estimation accuracy. It was also shown that having a sufficient amount of analog data from the external system is sufficient to ensure accurate internal state estimation accuracy. Further increases in the amount of analog data exchanged over the same geographical area no longer help to improve state estimation any further.

In this chapter, the focus will shift to the exchange of data with different areas of the external system. In an ideal situation, the control center would communicate with all its neighbors to carry out data exchange, and would therefore be able to obtain information on the entire external model. The real situation tends to deviate from the ideal one, and the internal system may not always be able to obtain data from all of its neighbors. The idea here is to simulate the situation where communication is only possible with some of the neighbors, such that no communication is performed with one or more of the neighbors. This leads to data exchange being performed with only certain areas of the external system. Different scenarios are set up in this chapter to study the effects of data exchange on internal state estimation in the aforementioned situation.

3.2. Data Exchange with select areas of the external system

The IEEE-118 bus system will be used as the test bed in this section, and the external system is divided into two areas as shown in Figure 3. The internal system is denoted as Area I, while the two portions in the external system are denoted as Areas IIA and IIB respectively. Detailed information regarding this configuration of the IEEE-118 bus system is provided in TABLE II.

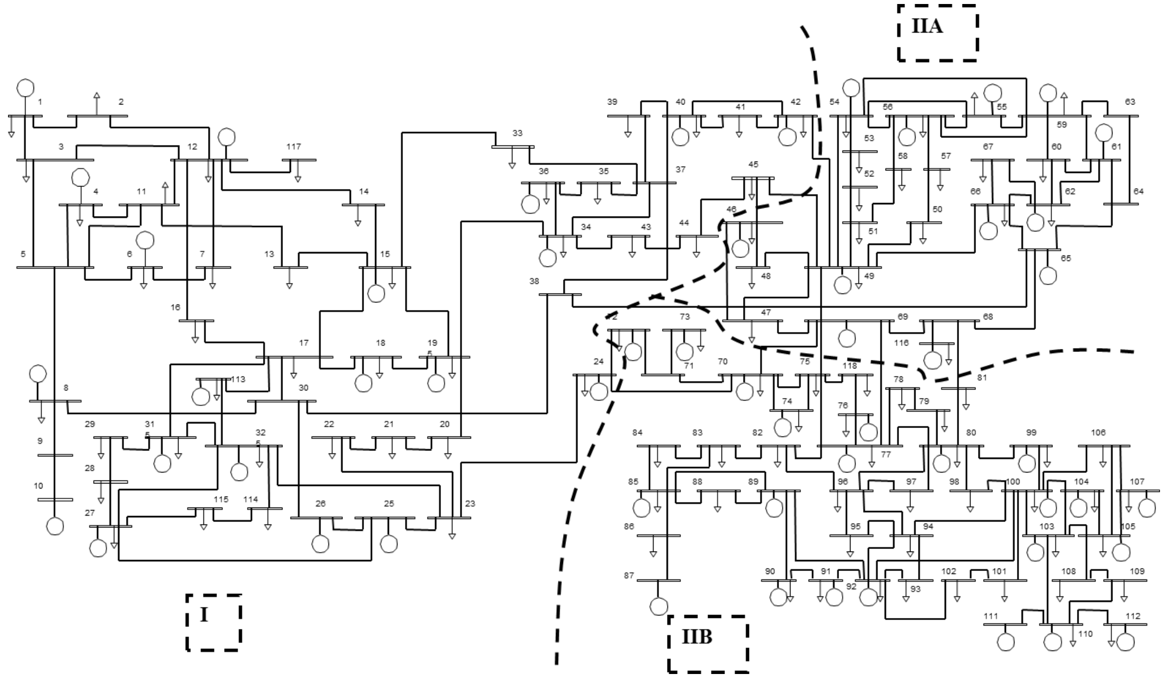

Figure 3. IEEE-118 bus system diagram (Configuration 1)

TABLE II. Details of IEEE-118 bus system (Configuration 1)

Buses in Area I (internal system)	Buses in Area IIA	Buses in Area IIB
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 113, 114, 115, 117	46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 116	70, 71, 72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 111, 112, 118
Tie lines between Areas I and IIA	Tie lines between Areas I and IIB	Tie lines between Areas IIA and IIB
38-65, 42-49, 45-46, 45-49	24-70, 24-72	68-82, 69-70, 69-75, 69-77

Three scenarios are created for the comparison of different levels of data exchange on internal state estimation accuracy. In the first scenario (3A), there is no data exchange at all, and pseudo measurements are created for the entire external system to ensure that the system remains observable. It is worth noting that these pseudo measurements are created based on the base case operating conditions. In the second scenario (3B), it is assumed that data exchange can only be performed with Area IIA and there is no communication with Area IIB. Hence, real-time data can only be obtained for Area IIA and pseudo measurements are created for buses in Area IIB to ensure that the system remains observable. In the third scenario (3C), the ideal situation is simulated and data exchange is performed with both Areas IIA and IIB so that real-time data from the entire external system is available during internal state estimation.

Cases to be studied are created as follows. A line outage is incurred for each line in the external system, and this line outage will be included into the list of cases to be studied in the event that the power flow successfully converges despite this topology change. It is impractical to illustrate the state estimation accuracy metric for every single case studied here, and the mean value of the metric J_{118} for all the cases which are run are illustrated in TABLE III.

TABLE III. Study of effects of data exchange with select areas of the external system (Testbed system: IEEE 118 bus system (Configuration 1))

Scenario	Data exchanged with external system	J_{118} (Mean)
3A	• No data exchange. • Pseudo measurements are created for buses in Areas IIA and IIB to ensure the system remains observable	$2.188\text{x}10^{-1}$
3B	• Real and reactive power injection measurements at each bus in Area IIA • Pseudo measurements are created for buses in Areas IIB to	$2.065\text{x}10^{-3}$

	ensure the system remains observable - Topology data of the Area IIA	
3C	- Real and reactive power injection measurements at each bus in the external system (Areas IIA and IIB) - Topology data of the external system (Areas IIA and IIB)	5.0x10^{-5}

Once again, it can be observed that the lack of data exchange can lead to large errors in internal state estimation in many cases. This is because the pseudo measurements used for the external system fail to reflect the actual operating conditions in the external system. In general, it appears that data exchange with a portion of the external system reduces the amount in which the internal state estimation accuracy deteriorates, but the level of accuracy may not be sufficient for ensuring accurate contingency analysis either. As observed in the studies in the previous chapter, the internal state estimation solution is practically identical to the exact solution when full data exchange with the external system is implemented.

In some cases, it is also possible to obtain very accurate state estimation solutions even when communication with all neighbors cannot be implemented and data exchange only occurs with a part of the external system. This specific phenomenon can be observed for the case where there is a topology change on line 49-66. The results are illustrated in TABLE IV below. For this specific case, it is noted that the state estimation accuracy metric drops to the order of 10^{-5} already when data exchange is only performed with a portion of the external system (Area IIA). The value of the accuracy metric is comparable to that when data exchange with the entire external system is implemented.

TABLE IV. Study of effects of data exchange with select areas of the external system for a topology change on line 49-66 of the external system (Testbed system: IEEE-118 bus system (Configuration 1))

Scenario	Data exchanged with external system	J_{118}
3A	• No data exchange. • Pseudo measurements are created for buses in Areas IIA and IIB to ensure the system remains observable	1.74x10^{-2}
3B	• Real and reactive power injection measurements at each bus in Area IIA • Pseudo measurements are created for buses in Areas IIB to ensure the system remains observable • Topology data of the Area IIA	2.6x10^{-5}
3C	• Real and reactive power injection measurements at each bus in the external system (Areas IIA and IIB) • Topology data of the external system (Areas IIA and IIB)	1.4x10^{-5}

An interesting point to note is that despite the lack of data exchange with one of the areas of the external system in Scenario 3B, the internal system is aware of the topology change in the external system, since the line 49-66 is in Area IIA, and this may have played a role in preventing the deterioration of internal state estimation accuracy. It is also worth noting that there are several cases where the topology change in the external system does not lead to large changes in the system operating conditions, and hence, the effects of data exchange on improving internal system state estimation are not obvious for those cases.

3.3. Further investigation on effects of data exchange with select areas of the external system

The results in the previous subsection provided some insight on the effects of data exchange with only certain areas of the external system on internal state estimation accuracy. It was also observed that having correct topology knowledge may play a role in preventing state estimation results from deteriorating despite not having full data exchange with the entire external system. In this section, further investigation on the effects of data exchange with portions of the external system will be studied, with some emphasis placed on investigating the importance of topology information for improving internal state estimation accuracy.

A second configuration of the IEEE-118 bus system is created and is illustrated in Figure 4. Detailed information regarding this configuration of the IEEE-118 bus system is provided in TABLE V.

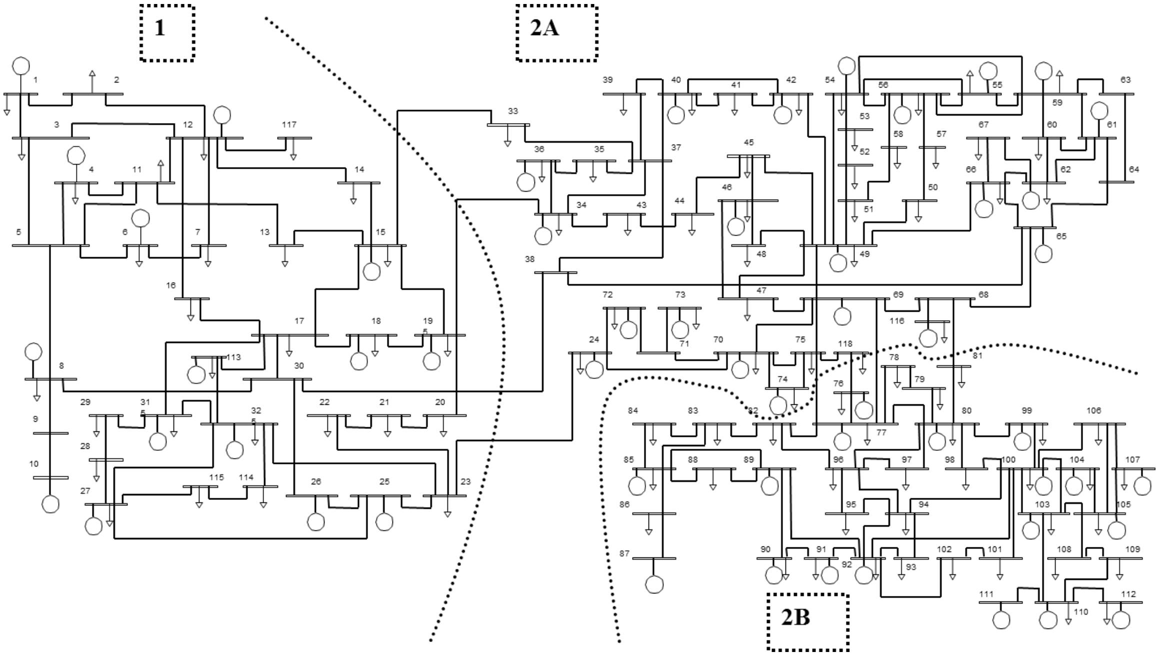

Figure 4. IEEE-118 bus system diagram (Configuration 2)

TABLE V. Details of IEEE-118 bus system (Configuration 2)

Buses in Area 1 (internal system)	Buses in Area 2A	Buses in Area 2B
1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 25, 26, 27, 28, 29, 30, 31, 32, 113, 114, 115, 117	33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61, 62, 63, 64, 65, 66, 67, 68, 69, 70, 71, 72, 73, 74, 75, 116, 118	76, 77, 78, 79, 80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94, 95, 96, 97, 98, 99, 100, 101, 102, 103, 104, 105, 106, 107, 108, 109, 110, 111, 112

Tie lines between Areas 1 and 2A	Tie lines between Areas 1 and 2B	Tie lines between Areas 2A and 2B
15-33, 19-34, 30-38, 23-24	N/A	68-81,69-77,75-77, 76-118

For this configuration of the IEEE-118 bus system, the internal system (Area 1) is only directly connected to one of the areas of the external system (Area 2A), while Area 2B is a further neighbor with no direct branch connections to the internal system.

Several scenarios are created for the purpose of this study, and they are listed in TABLE VI. In scenario 3E, where data exchange is only performed with a portion of the external system, it is assumed that communication is lost, or not possible with the nearer neighbor (Area 2A), and hence, data exchange is only performed with Area 2B.

TABLE VI. Scenarios for investigation of effects of data exchange with select areas of the external system (Testbed system: IEEE-118 bus system (Configuration 2))

Scenario	Data exchanged with external system
3D	- No data exchange with Area 2A and 2B - Pseudo measurements are created at external buses to ensure system remains observable
3E	- Real and reactive power injection measurements in Area 2B - System topology data in Area 2B - Pseudo measurements are created for buses in Area 2A to ensure that the system remains observable
3F	- Real and reactive power injection measurements in Areas 2A and 2B - System topology data in Areas 2A and 2B
3G	- Voltages, real and reactive power injections and flow measurements in Areas 2A and 2B - System topology data in Areas 2A and 2B

Cases are created in a manner similar to those in previous sections. It is worth noting that in this set of studies, the line outages which will be considered are all in Area 2A, which is the area with which no data is exchanged in Scenario 3E. This implies that when internal state estimation is performed in Scenario 3E, the topology data used by the internal state estimator will be incorrect, since Area 1 has no knowledge of the topology change incurred in the external system. The purpose of selecting cases in this method is to develop greater insight in the significance of correct topology data when performing state estimation.

The mean values of the state estimation accuracy metrics for all the cases are obtained and are shown in TABLE VII.

TABLE VII. Study of effects of data exchange with select areas of the external system (Testbed system: IEEE-118 bus system (Configuration 2))

Scenario	J_{118} (Mean)
3D	1.85×10^{-2}
3E	1.86×10^{-2}
3F	6.15×10^{-5}
3G	1.97×10^{-5}

As expected, large errors are observed in Scenario 3D when no data exchange is performed. The interesting observation is that in Scenario 3E, having data exchange with some areas of the external system does not necessarily help improve internal state estimation accuracy when the topology data used by the state estimator is incorrect. In Scenario 3E, analog measurements are obtained from Area 2B during data exchange, but the mean of the state estimation accuracy metric indicates no improvement in state estimation accuracy. In Scenarios 3F and 3G, it is observed that full exchange with the entire external system provides accurate state estimation results once again.

Further perusal in the state estimation accuracy metric obtained for each external topology change reveals that there are some cases where having data exchange with portions of the external system leads to slight improvements in internal state estimation accuracy. There are also numerous cases where the external topology change does not affect the system operating conditions sufficiently, and hence, the state estimator remains fairly accurate regardless of whether data exchange is performed or not. The cases of interest, however, are the ones where having data exchange with portions of the external system does not improve internal state estimation at all.

These particular cases of interest are illustrated in TABLE VIII below. They represent topology changes on lines 42-49, 69-70 and 69-75 in Area 2A respectively.

TABLE VIII. Study of effects of data exchange with select areas of the external system (Testbed system: IEEE-118 bus system (Configuration 2), specific external line outages)

	J_{118} for topology change on line		
Scenario	42-49	69-70	69-75
3D	2.102×10^{-1}	7.949×10^{-2}	1.824×10^{-2}
3E	2.097×10^{1}	7.811×10^{-2}	1.907×10^{-2}
3F	9.96×10^{-5}	9.06×10^{-5}	1.16×10^{-5}
3G	2.04×10^{-5}	1.15×10^{-5}	1.62×10^{-5}

In these particular cases of interest, it is observed that implementing data exchange with only portions of the external system may lead to large errors in internal state estimation accuracy. In the event where there is a external outage on line 69-75, it is even possible for the state estimation results to deteriorate such that having no data exchange is slightly better than having partial data exchange.

These results provide insight in reminding control centers that having data exchange with only certain neighboring areas without understanding the operating conditions of entire external system may potentially lead to large errors in state estimation results. For the above cases, the reader is reminded that the topology changes occur in Area 2A, where data exchange is not implemented. Hence, the topology changes are not known to the internal system state estimator. This illustrates that having knowledge of the analog data over a larger portion of the external system may not have any effect on improving the accuracy of internal state estimation when incorrect topology data is used.

From the above results, it was noted again that certain topology changes external system do not lead to sufficiently large changes in the system operating conditions. Such cases are of little interest, since the goal in this dissertation is to observe the effects of data exchange on internal state estimation accuracy. In order to perform such studies, it is necessary to study cases where there is sufficient change in system operating conditions that the power flow solution of the system will differ substantially from the base case. If a change in topology does not lead to a sufficiently large change in the system operating conditions, the pseudo measurements used in scenarios where there is no data exchange would be practically the same as the actual measurements exchanged. This would undermine the effects of data exchange on internal state estimation accuracy, since the representation of the external model is already accurate with the pseudo measurements alone.

Moreover, it is noted once again that having sufficient real-time measurements over the entire external system suffices to ensure the state estimation results are accurate, and that having additional real-time measurements is unnecessary. Based on the observations from the studies above, only real and reactive power injection measurements will be exchanged during SCADA data exchange in ensuing sections and chapters of this dissertation.

3.4. Study of effects of data exchange with select areas of the external system on 1648 bus system

Studies to study the effects of data exchange with only certain areas of the external system are then extended to the 1648 bus system. The goal is to observe if similar trends can be observed for the large system. The large power system to be used in this section is the 1648 bus system. The system is grouped into 4 areas, as shown in Figure 5 below, and details of the system are provided in TABLE IX and TABLE X below. Area 1 represents the internal system and Area 2-4 represent the neighbors of the internal system. Note that Figure 5 merely shows the zones of the system to illustrate that each zone is interconnected to all other zones.

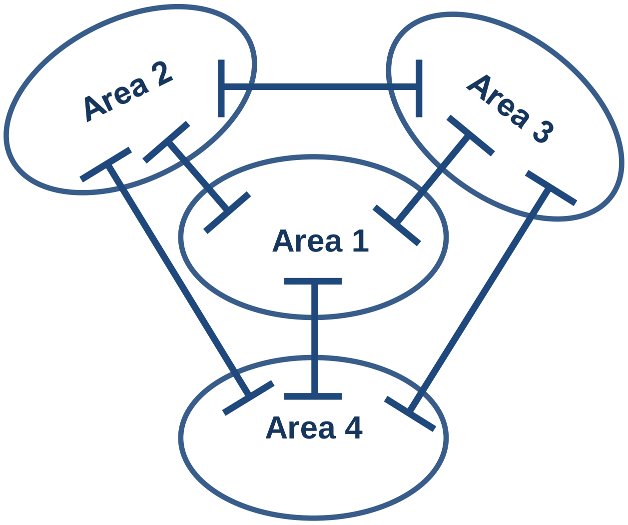

Figure 5. Schematics of the configuration of the 1648 bus system.

TABLE IX. Details of the 1648 bus system (Buses)

Areas	Number of buses	Bus numbers
1	411	1-21, 51-75, 271, 458-460, 875-1199, 1582-1630
2	427	76-88, 461-874
3	394	1189-1582
4	416	22-50, 89-270, 272-457, 1583, 1631-1648

TABLE X. Details of the 1648 bus system (Lines)

Areas		Number of tie lines between Areas a and b
a	b	
1	2	48
1	3	45
1	4	34
2	3	11
2	4	7
3	4	1

Several scenarios are created for the study of the effects of data exchange with different portions of the external system on internal state estimation accuracy, and they are listed in TABLE XI.

TABLE XI. Scenarios for investigation of effects of data exchange with select areas of the external system (Testbed system: 1648 bus system)

Scenario	Data exchanged with external system
3H	- No data exchange - Pseudo measurements are created at external buses to ensure system remains observable
3I	- Real and reactive power injection measurements in Area 2 - System topology data in Area 2 - Pseudo measurements are created for buses in Areas 3 and 4 to ensure that the system remains observable
3J	- Real and reactive power injection measurements in Area 3 - System topology data in Area 3 - Pseudo measurements are created for buses in Areas 2 and 4 to ensure that the system remains observable
3K	- Real and reactive power injection measurements in Area 4 - System topology data in Area 4 - Pseudo measurements are created for buses in Areas 3 and 4 to ensure that the system remains observable
3L	- Real and reactive power injection measurements in Areas 2 and 3 - System topology data in Areas 2 and 3 - Pseudo measurements are created for buses in Area 4 to ensure that the system remains observable
3M	- Real and reactive power injection measurements in Areas 2 and 4 - System topology data in Areas 2 and 4 - Pseudo measurements are created for buses in Area 3 to ensure that the system remains observable
3N	- Real and reactive power injection measurements in Areas 3 and 4 - System topology data in Areas 3 and 4 - Pseudo measurements are created for buses in Area 2 to ensure that the system remains observable

3O	- Real and reactive power injection measurements in Areas 2, 3 and 4 - System topology data in Areas 2, 3 and 4

For the 1648 bus system, it is impractical to create cases for every line outage in the external system because of the excessive computational burden. From previous sections, it was noted that cases of interest are those which would lead to large changes in the system operating conditions.

Intuitively, line outages occurring further away from the internal system have less effect on the operating conditions around the internal system as compared to those near the internal system. Hence, one of the criteria for selecting topology changes to create cases for the large system is that the topology change is sufficiently close to the internal system. Moreover, line outages of heavily loaded lines tend to create larger perturbations in system operating conditions, and hence, another criterion for selecting topology changes is that the lines is transferring a sufficient amount of real power in the base case.

There are 2602 branches in the 1638 bus system and all external branches with a real power flow of more than 100 MW in the base case operating conditions are selected for further consideration. Then, these branches are further checked such that only branches which are connected by buses within 3 neighbors' distance from the internal boundary buses are considered. Obviously, lines connecting boundary buses to the external system would be considered too. The following criteria provide a total of 62 branch outages to create cases for the study of data exchange on internal state estimation.

For the IEEE-118 bus system, the metric proposed in Equation (2-10) was used and is illustrated below for the convenience of the reader.

$$J_{118} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^*\right] \qquad \text{(3-1) or (2-10)}$$

where $\vec{V_i}$ is the estimated complex voltage at bus *i*

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the power flow solution

N is the number of internal system buses

During the simulations for the large system, it was noted that this metric does not illustrates trends in a very obvious way, so a modification of the above metric was performed. The metric to be used for the 1648 bus system is shown below:

$$J_{1648} = \frac{1}{N}\sum_{i=1}^{N}\sqrt{\left[\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^*\right]} \qquad \text{(3-2)}$$

where $\vec{V_i}$ is the estimated complex voltage at bus *i*

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the power flow solution

N is the number of internal system buses

The above metric takes the difference between the state estimated complex voltage and the exact complex voltage at each internal bus of the system, and multiples this value by its complete conjugate so that the error appears in the form of a real number. The square root of this real number is taken, and the sum of all these numbers is then divided by the number of buses in the internal system. *N* represents the number of buses in the internal system only, since only the buses within one's own control area are of interest. This metric has the similar features and drawbacks, and hence, boundary buses errors are still monitored in the study of the large system.

For the studies on the 1648 bus system, it is impractical to illustrate the state estimation metrics for all the cases for all the listed scenarios, and so, results will be summarized with the mean of the modified state estimation metric J_{1648} from all the cases for each scenario. The results are illustrated in TABLE XII.

TABLE XII. Study of effects of data exchange with select areas of the external system (Testbed system: 1648 bus system)

		All lines
Scenario	Data Exchange with Areas	J_{1648} (Mean)
3H	None	0.312949
3I	2	0.012924
3J	3	0.265236
3K	4	0.016891
3L	2,3	0.003576
3M	2,4	0.016171
3N	3,4	0.006043
3O	2,3,4	0.003535

As in the case for the IEEE-118 bus system, the lack of data exchange will lead to large errors in internal state estimation, as shown in Scenario 3H. In fact, the large value indicated implies that the SE has not converged to a practical solution successfully. Once again, data exchange with the entire external system (Scenario 3O) gives very accurate state estimation results as expected. For scenarios 3I to 3K, where data exchange is only performed with one of the neighbors, the internal state estimation results illustrate moderate errors from the actual power flow solution. For cases where data exchange is with Area 3 only, the state estimation accuracy metric attains a very large value in general, implying that the internal SE solution does not converge to a practical solution successfully.

For cases 3L to 3N, data exchange is performed with two of the internal system's neighboring areas, and it can be seen that the errors are reduced already. For data exchange with Areas 2 and 3 or Areas 3 and 4 it appears that the internal state estimator solutions are fairly accurate already. However, the internal state estimator solutions appear to have moderate errors when data exchange is with Areas 2 and 4. These moderate errors are at approximately the same level of those when data is only exchanged with only one of the neighbors of the internal system.

Further perusal into the data itself brings up the fact that for all the cases where the error appears to be moderately large, the state estimator has not actually converged. While the results for the internal system appear reasonable, there are some results in the external system which are totally unreasonable. This shows that in using the full external model, there must be sufficient real-time data across the system to ensure that accurate state estimation solutions can be obtained. Needless to say, this real-time data includes both analog measurements and the topology data of the system. The effects of incorrect topology data on state estimation accuracy will be studied in later sections and are not discussed here.

For most of these cases, only scenarios 3L, 3N and 3O have state estimation results which are guaranteed to converge, and these will be studied in greater detail in later chapters where the effects of data exchange on ensuing contingency analysis are investigated.

It is worth noting that these problems where the state estimator does not converge when the external model data is erroneous were not observed for the IEEE-118 bus system. It is believed that this is because of the relatively small size of the IEEE-118 bus system and because of the fact the line outages on that test system do not change the system operating conditions as much as they would on the 1648 bus system.

Some cases are further investigated as certain trends similar to those from the IEEE-118 bus testbed studies can be observed. In this further analysis, Scenarios 3H to 3K will not be included, since it is already noted that having data exchange with only one of the neighbors is insufficient to provide accurate state estimation solutions.

The mean values of the state estimation accuracy metric listed in TABLE XII are for all the line outage cases which were considered. This does not provide much insight on whether knowledge of external system topology affects state estimation accuracy since the external line outages are in different areas of the external system. Therefore, the cases are rearranged such that external line outages in the same area are grouped together, and the results of state estimation are studied in further detail.

The results for external line outages in Area 3 are shown in TABLE XIII. From the results, it can be seen that the state estimation results are fairly accurate when data exchange is performed with either Areas 2 and 3, Areas 3 and 4 or the entire external system. However, relatively large errors can be observed when data exchange is with Areas 2 and 4. In these cases, it can be seen that exchanging data with neighbors where the external topology change does not occur may not necessarily help improve state estimation accuracy of the internal system. This is similar to the trends noted for the IEEE-118 bus system.

TABLE XIII. Study of effects of data exchange with select areas of the external system (Testbed system: 1648 bus system, External line outages in Area 3)

		Zone 3-3lines (16)
Scenario	Data Exchange with Areas	J_{1648}(Mean)
3L	2,3	0.003941
3M	2,4	0.021123
3N	3,4	0.00453
3O	2,3,4	0.003182

As in the case for the IEEE-118 bus system, there are cases where difference in the mean values of the state estimation accuracy is not so obvious for different levels of data exchange (Scenarios 3L, 3M, 3N, 3O). To further investigate the importance of correct topology data on state estimation accuracy during data exchange with the external system, some studies are conducted in latter chapters of this dissertation.

3.5. Summary

In this chapter, the effects of data exchange with certain areas of the external system on internal state estimation accuracy are studied. The studies are first performed on 2 configurations of the IEEE-118 bus system. In the first configuration, the internal system is directly connected to both areas of the external system, and in the second configuration one of the areas of the external system has no direct branch connections with the internal system. It is noted that the lack of data exchange can lead to large errors in state estimation accuracy when the actual operating conditions of the system deviate sufficiently from the base case conditions. This allows further studies to be focused on cases where changes such as line outages lead to sufficiently large changes in system operating conditions.

For the IEEE-118 bus system, it is observed that performing data exchange with only certain areas of the external system does not always guarantee an increase in state estimation accuracy of the internal system. This observation is more pronounced in cases where the topology knowledge of the system is still incorrect despite obtaining analog data over a larger area of the system.

The studies were extended to the 1648 bus system to observe if similar trends could be obtained. It was once again observed that the lack of data exchange would lead to large errors in state estimation. In fact, when the system operating conditions are far from the base case conditions, the pseudo measurements employed to maintain system observability fail to represent the actual conditions, and it is possible for the state estimator to fail to converge. Data exchange with small portions of the external system no longer guarantee convergence either when the real-time measurements obtained during data exchange do not cover a large enough portion of the external system. This illustrates one of the difficulties in using the full external model, which is that sufficient real-time data across the system must be available to ensure accurate state estimation solutions. In cases where data exchange is implemented with a larger portion of the external system, it is possible to obtain accurate state estimation results. It appears that correct topology knowledge plays a role in ensuring that accurate state estimation results can be obtained, as was already observed in tests for the IEEE-118 bus system. It was therefore proposed that further tests be conducted to investigate the effects of incorrect topology data on state estimation accuracy, and details of such tests will be covered in ensuing chapters of this dissertation.

4. EFFECTS OF EXCHANGE OF DIFFERENT TYPES OF DATA ON INTERNAL STATE ESTIMATION

4.1. Introduction

In the previous chapters of this dissertation, it was assumed that SCADA data, comprising measurements obtained directly from the external system is exchanged when data exchange is implemented. In this chapter, the exchange of SCADA data versus state estimated data will be studied. This investigation will be conducted using an approach similar to that in previous chapters, where a list of topology changes in the external system will be applied and various scenarios representing different types of data exchange will also be created to compare the accuracy of internal state estimation. Moreover, the effects of data exchange where the topology processor of the external system is malfunctioning will also be studied.

4.1.1. SCADA data exchange versus state estimated data exchange

In the event where SCADA data exchange is implemented, state estimation of the full external model is required. For state estimated data exchange, state estimation of the full external model is no longer required and the internal system is solved only up to the external boundary buses. The state estimated voltages of the boundary buses received from the external area are assumed to have a very high confidence level (say, two magnitudes higher than the internal area measurements), which would have the effect of fixing the boundary bus values during internal state estimation.

The exchange of state estimated data is simulated in our tests through the process described below. The internal system is denoted as Area 1, while the external system is denoted as Area 2.

1. The internal state estimator for Area 1 is solved, and this solution and data is sent to Area 2.
2. Area 2 then runs its state estimator based on its internal measurements and Area 1's state estimated data, and sends the data back to Area 1.
3. Area 1 runs its state estimator again based on the state estimated data from Area 2 in step 2 above, and the results are used to obtain the values for the state estimation accuracy metric, which will be used for comparison with other scenarios.

In the above simulation process, it should be noted that the data used by Area 1 in performing step 1 is dependent on events happening in the power system. Specifically, the data to be used is dependent on the time that the topology change occurs. It is possible that the topology change occurs prior to the time that Area 1 receives Area 2's state estimated data, in which case, the topology data and state estimated solution obtained by Area 1 would already be correct and up to date.

In another scenario, the topology change may occur after Area 1 receives Area 2's state estimated data, such that the data used by Area 1 to run its internal state estimator in step 1 would not be up to date.

Both possibilities are considered in designing scenarios to study the effects of SCADA data exchange versus state estimated data exchange on internal state estimation. For the purpose of this study, the topology change is assumed to always occur before step 2 of the process. As a result, the data received by Area 1 in step 3 of the simulation process will always have accounted for the topology change which had already occurred before Area 2 runs its state estimator in step 2. Obviously, the above complications do not occur when SCADA data is exchanged, since this type of data exchange would contain both the measurement and topology data and the exchange of SCADA data is complete in one pass. The scenarios created for the study of the effects of exchanging SCADA data versus state estimated data on internal state estimation accuracy are shown in TABLE XIV.

TABLE XIV. Scenarios for comparing the effects of SCADA data exchange versus state estimated data exchange on state estimation accuracy (Testbed system: IEEE-118 bus system)

Scenario	Type of data Exchange
4A	No data exchange
4B	SCADA data exchange with external system
4C	State Estimated Data Exchange where data is initially not up to date
4D	State Estimated Data Exchange where data is initially up to date

From the simulations, it is noted that the state estimator solutions obtained in scenarios 4B and 4D are basically identical to the exact solution. This is reasonable, since these two scenarios represent the ideal situation where the data exchanged is correct and up to date, and intuitively, the state estimator solutions should be correct as well.

The state estimation accuracy metric for all 4 scenarios are relatively small and do not show great difference in accuracy, and are therefore not illustrated here. Further investigation into the actual state estimation results indicated that large errors may appear at the boundary buses in the case where state estimated data which is exchanged is not up-to-date. Therefore, the mean errors at both the internal and external boundary buses are noted and illustrated for cases where the errors are significantly large.

These cases include topology changes on lines 49-66, 69-70 and 69-75 on configuration 1 of the IEEE-118 bus system and topology changes on lines 42-49 and 69-70 on configuration 2 of the IEEE-118 bus system. The mean values of the absolute errors of the voltage at both internal and external boundary buses for these cases are illustrated in TABLE XV.

TABLE XV. Mean Errors at Boundary Buses for Scenarios 4A to 4D (Testbed System: IEEE-118 bus system, Specific Cases)

Topology change on line	Scenario 4A	Scenario 4B	Scenario 4C	Scenario 4D
Configuration 1				
49-66	$4.42\text{x}10^{-2}$	$6.20\text{x}10^{-4}$	$2.31\text{x}10^{-2}$	$3.48\text{x}10^{-4}$
69-70	$4.47\text{x}10^{-2}$	$7.83\text{x}10^{-4}$	$1.46\text{x}10^{-2}$	$1.87\text{x}10^{-4}$
69-75	$2.11\text{x}10^{-2}$	$6.24\text{x}10^{-4}$	$2.54\text{x}10^{-3}$	$3.70\text{x}10^{-4}$
Configuration 2				
42-49	$7.99\text{x}10^{-2}$	$7.92\text{x}10^{-4}$	$1.12\text{x}10^{-2}$	$2.80\text{x}10^{-4}$
69-70	$4.83\text{x}10^{-2}$	$6.20\text{x}10^{-4}$	$6.68\text{x}10^{-3}$	$2.28\text{x}10^{-4}$

It can be observed from the above cases that the errors at the boundary bus are large for Scenario 4A, which is expected since there is no data exchange. Scenarios 4B and 4D represent the ideal situations where accurate and up to date data is exchanged, and so, the errors are practically equal to zero, which confirms that exchanging either state estimated data or SCADA data which is up to date give state estimation results practically equivalent to the exact solution. In Scenario 4C, the data used by Area 1 initially is incorrect, and this appears to have some effect on the state estimation results obtained at the end of the state estimated data exchange process and there are slightly larger errors at some boundary cases for each case. However, the errors are still less than those obtained when no data is exchanged at all.

4.2. Effects of topology errors during data exchange

4.2.1. IEEE-118 bus system with both SCADA and state estimated data exchange

The effects of topology errors in the external system’s topology processor will next be investigated. The situation becomes one where the topology processor assumes the base case topology even when there is a line outage, meaning that the topology change is not seen during internal state estimation even when data exchange with the external system is implemented.

In scenarios where SCADA data is exchanged, this implies that all analog measurements obtained by Area 1 would be up to date, but the internal state estimator would be run using incorrect system topology data.

In scenarios where state estimated data exchange is implemented, this implies that in step 2 of the state estimated data exchange process, Area 2 will be using updated measurements in its own area, together with Area 1’s state estimation results from step 1, but the topology data used during Area 2’s state estimation would be incorrect. Hence, the state estimation results of Area 2 which are sent back to Area 1 may also be wrong. The objective of this subsection is to observe the effects of these errors on Area 1’s internal state estimation in step 3 of the state estimated data exchange process.

The same scenarios which were listed in TABLE XIV are used again, and the mean values of the absolute errors of the voltage at both internal and external boundary buses for these cases are illustrated in TABLE XVI.

TABLE XVI. Mean Errors at Boundary Buses for Scenarios 4A to 4D with errors in external system's topology processor (Testbed System: IEEE-118 bus system, Specific Cases)

Topology change on line	Scenario 4A	Scenario 4B	Scenario 4C	Scenario 4D
Configuration 1				
49-66	4.42×10^{-2}	1.16×10^{-2}	1.82×10^{-2}	2.21×10^{-3}
69-70	4.27×10^{-2}	3.89×10^{-2}	1.53×10^{-2}	3.16×10^{-3}
Configuration 2				
42-49	7.99×10^{-2}	6.57×10^{-2}	1.14×10^{-2}	5.17×10^{-4}

It can be observed that the errors at the boundary buses remain the same in Scenario 4A as in those in section 4.1, since the internal system has no knowledge of the external system regardless of whether the topology processor in the external system is faulty or not. However, the errors at the boundary buses for Scenario 4B become much greater, and in the listed cases, they even get close to those when there is no data exchange. This shows again that it is possible to obtain large errors in the state estimation process even when correct analog data is obtained if the topology data is incorrect. In Scenario 4C, the state estimation results are still fairly accurate even when the external system has a topology error, as this topology error does not directly appear to the internal system state estimator since it is not required for the entire external system model to be solved during internal state estimation. The errors caused by the incorrect SE results of the external system appear to the internal system as analog errors at the boundary buses of the reduced external system. Moreover, scenario 4D is set up in a way that the topology processor is still operating in the previous cycle and only starts to malfunction in the current cycle. This leads us to believe that having correct topology knowledge in previous cycles helps alleviate errors caused by incorrect knowledge in current cycles. The way in which Scenario

4C is set up causes the topology data to be wrong in both the current cycle and the previous cycle, so the error at the boundary buses can become large in some cases as observed in the tables.

4.2.2. 1648 bus system with SCADA data exchange

The studies of the effects of topology errors in the external system's topology processor are then extended to the 1648 bus system. In the previous section, it was noted that the effects of topology errors on state estimated data exchange appear less pronounced since the internal state estimator only solves for the system up to the boundary buses and the topology errors only appear as analog errors at the boundary buses. Therefore, for the 1648 bus system, only scenarios where SCADA data is exchanged will be investigated. The effects of different levels of data exchange on state estimation accuracy for the 1648 bus system have already been studied in Chapter 3, and the same system will be used here. The configuration is illustrated here once again for the convenience of the reader.

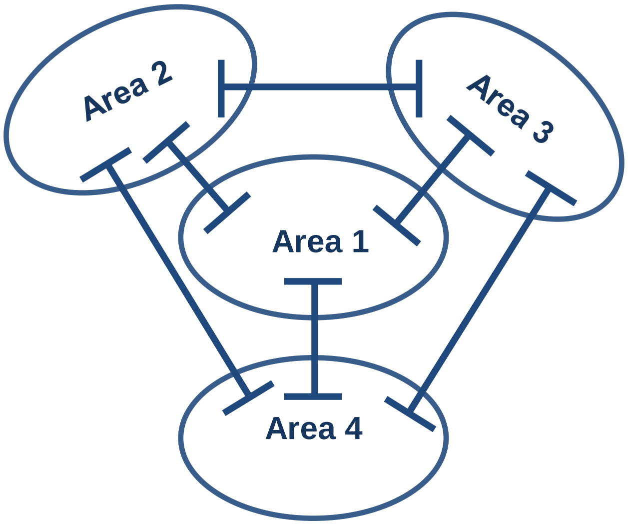

Figure 6. Schematics of the configuration of the 1648 bus system

TABLE XVII. Details of the 1648 bus system (buses)

Areas	Number of buses	Bus numbers
1	411	1-21, 51-75, 271, 458-460, 875-1199, 1582-1630
2	427	76-88, 461-874
3	394	1189-1582
4	416	22-50, 89-270, 272-457, 1583, 1631-1648

In Chapter 3, it was shown that data exchange with at least two of the internal system's neighbors is necessary to obtain a reasonable state estimation solution. The scenarios which are created for the study of the effects of errors in topology data during data exchange on state estimation accuracy are shown in TABLE XVIII.

TABLE XVIII. Scenarios for investigation of the effects of topology errors on state estimation accuracy (Testbed system: 1648 bus system)

Scenario	Data exchanged with external system
4E	- Real and reactive power injection measurements in Areas 2 and 3 - System topology data in Areas 2 and 3 - Pseudo measurements are created for buses in Area 4 to ensure that the system remains observable
4F	- Real and reactive power injection measurements in Areas 2 and 4 - System topology data in Areas 2 and 4 - Pseudo measurements are created for buses in Area 3 to ensure that the system remains observable
4G	- Real and reactive power injection measurements in Areas 3 and 4 - System topology data in Areas 3 and 4 - Pseudo measurements are created for buses in Area 2 to ensure that the system remains observable
4H	- Real and reactive power injection measurements in Areas 2, 3 and 4 - System topology data in Areas 2, 3 and 4
4I	- Real and reactive power injection measurements in Areas 2 and 3 - Pseudo measurements are created for buses in Area 4 to ensure that the system remains observable - Areas 2 and 3 have errors in their topology processors and are unaware of any topology changes in these areas
4J	- Real and reactive power injection measurements in Areas 2 and 4 - Pseudo measurements are created for buses in Area 3 to ensure that the system remains observable - Areas 2 and 4 have errors in their topology processors and are unaware of any topology changes in these areas
4K	- Real and reactive power injection measurements in Areas 3 and 4 - Pseudo measurements are created for buses in Area 2 to ensure that the system remains observable

	- Areas 3 and 4 have errors in their topology processors and are unaware of any topology changes in these areas
4L	- Real and reactive power injection measurements in Areas 2, 3 and 4 - Areas 2, 3 and 4 have errors in their topology processors and are unaware of any topology changes in these areas

In Scenarios 4I to 4L, there is data exchange with at least two of the neighbors in the external system, meaning that the real-time analog data regarding these 2 neighbors is up to date. However, the topology error in the external system means that any topology changes in the external system will remain unknown to the internal system during state estimation. The results for all external line outages which are considered are shown in TABLE XIX below.

TABLE XIX. State Estimation accuracy metric for Scenarios 3H to 3O (Testbed System: 1648 bus system, all external line outages)

		All lines
Scenario	Data Exchange with Areas	J_{1648} (Mean)
4E	2,3	0.003576
4F	2,4	0.016171
4G	3,4	0.006043
4H	2,3,4	0.003535
4I	2,3 (with topology errors)	0.006439
4J	2,4 (with topology errors)	0.023278
4K	3,4 (with topology errors)	0.007566
4L	2,3,4 (with topology errors)	0.005984

It can be seen that the existence of topology errors in the external system's topology processor leads to deterioration in the state estimation results in general. The overall changes in the state estimation accuracy metric when state estimation is performed with incorrect topology data of the external system is not so large, so individual cases will be studied to gather greater insight. It is worth noting that for some cases, and for certain scenarios, the line outage may be in an area where there is no data exchange. For example, in the event that there is a line outage in Area 3, the values of the state estimation accuracy metric obtained for Scenarios 3I and 3M would be exactly the same. This is because in the topology change would not be known by the internal system regardless of whether there is an error in the external system's topology processor or not. Another issue is that not all cases may lead to large errors in state estimation when there is only partial data exchange, and these cases will contribute to the small changes in the mean values of the state estimation accuracy metric. As in the studies for the IEEE-118 bus system, it is more useful to consider several specific cases of interest to gain greater insight on the effects of topology errors on state estimation accuracy. These cases represent external line outages on lines 1-130, 243-246, 639-663, 656-687, 817-818, 817-867, 1218-1220, 1305-1319 and 1438-1543.

Line 1-130 is a tie line and hence, any topology change on this line should be known at all times. However, simulations are still performed to observe the effects of an error in the topology processor on state estimation accuracy. As observed in TABLE X, the state estimation accuracy metric increases for all cases where there is incorrect topology data.

TABLE XX. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 1-130)

External line outage: 1-130	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.001935	0.01505	0.003949	0.001785
Topology processor of external areas malfunctioning	0.010362	0.014896	0.015584	0.012556

Lines 639-663, 656-687, 817-818 and 817-867 are all in Area 2, and the results are shown in TABLE XX to TABLE XXIV. It can be seen that for these cases, there is no difference in the state estimation accuracy metric regardless of whether a topology error exists for scenarios when data exchange is only with areas 3 and 4 and that the state estimation results can have slightly large errors in these cases. For all other scenarios, it is observed that the state estimation results are significantly worse in the existence of errors in the external system's topology processor. The state estimation accuracy metric increases by a least an order in most cases.

TABLE XXI. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 639-663)

External line outage: 639-663	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.005192	0.017086	0.006006	0.004113
Topology processor of external areas malfunctioning	0.010559	0.020733	0.006006	0.009233

TABLE XXII. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 656-687)

External line outage: 656-687	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.002302	0.01168	0.010577	0.00246
Topology processor of external areas malfunctioning	0.01128	0.142204	0.010577	0.011038

TABLE XXIII. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 817-818)

External line outage: 817-818	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.005805	0.014064	0.021294	0.00302
Topology processor of external areas malfunctioning	0.025903	0.150544	0.021294	0.022853

TABLE XXIV. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 817-867)

External line outage: 817-867	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.001727	0.004178	0.028795	0.003703
Topology processor of external areas malfunctioning	0.015135	0.024505	0.028795	0.013569

Similar results can be observed for lines 1218-1220, 1305-1319 and 1548-1543, which are all in Area 3. From TABLE XXV to TABLE XXVIII, it can be seen that data exchange with Areas 2 and 4 provides erroneous results regardless of the existence of topology errors since this topology will be unknown to the internal system anyways as no data is exchanged with Area 3. For the other scenarios where data is exchanged with Area 3 and some other area, it can be seen that the state estimation tends to be much more erroneous when there is an error in the external system’s topology processor.

TABLE XXV. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 1218-1220)

External line outage: 1218-1220	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.002076	0.052603	0.007549	0.003028
Topology processor of external areas malfunctioning	0.006348	0.052603	0.013195	0.008613

TABLE XXVI. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 1305-1319)

External line outage: 1305-1319	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.003756	0.024425	0.004714	0.002781
Topology processor of external areas malfunctioning	0.014858	0.024425	0.02125	0.017487

TABLE XXVII. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 1438-1543)

External line outage: 1438-1543	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.003915	0.035459	0.004615	0.002791
Topology processor of external areas malfunctioning	0.016647	0.035459	0.011677	0.01424

Finally, the case for line 243-246 in Area 4 is also shown in TABLE XXVIII below. The results are similar in that the existence of errors in the external system's topology processor may lead to large errors in state estimation.

TABLE XXVIII. State Estimation accuracy metrics for investigation of effects of topology errors on state estimation accuracy (Testbed System: 1648 bus system, topology change on line 243-246)

External line outage: 243-246	Data exchange with external areas			
	2,3	2,4	3,4	2,3,4
	J_{1648}	J_{1648}	J_{1648}	J_{1648}
Topology processor of external areas functioning properly	0.005228	0.38949	0.004725	0.00537
Topology processor of external areas malfunctioning	0.005228	0.022962	0.011923	0.013328

4.3. Summary

In this chapter, the exchange of SCADA data versus the exchange of state estimated data on state estimation accuracy has been studied. It is shown on the IEEE-118 bus system that exchanging up to date SCADA data or state estimated data both lead to very accurate state estimation results. The main difference in exchanging SCADA data and state estimated data is in how much of the system is solved for during state estimation. It appears that exchanging state estimated data alleviates the issue of errors in the external system’s topology processor slightly since the topology error does not show up in the internal system’s topology data and just shows up as analog errors at the boundary buses because the system is only solved up to the boundary buses.

The effects of topology errors on SCADA data exchange are also investigated on the 1648 bus system, and scenarios are created to illustrate the effects of incorrect topology knowledge on state estimation. It is noted that the existence of topology errors during state estimation can lead to large errors in state estimation results even when real-time analog data is obtained from neighboring studies. These studies once again illustrate the importance of having correct topology data during the state estimation process.

5. EFFECTS ON HOW MUCH OF EXTERNAL MODEL IS REQUIRED FOR ACCURATE STATE ESTIMATION AND ENSUING CONTINGENCY ANALYSIS

5.1. Introduction

In previous chapters, studies have been performed to investigate the effects of various amounts and types of data exchange on internal state estimation accuracy. In Chapter 2, it was noted that using a reduced external model may lead to large errors in state estimation when there are changes in the operating conditions of the power system. It was also noted that data exchange with the external system as a detailed model helped improve internal state estimation accuracy. In Chapter 3, it was noted that only having data exchange with portions of the external system may sometimes lead to poor state estimation results, which imply that having data exchange over a larger area of the external system would be more helpful in ensuring a high level of accuracy for the internal state estimator.

In this chapter, the focus will be on determining how much of the external model is actually required for accurate state estimation and ensuing EMS functions, such as contingency analysis.

5.1.1. Approach

In order to determine how much of the external model is actually needed for accurate state estimation, a method has to be determined to divide the external system into various layers, which would represent the amount of external system that is solved for during state estimation. It is worth noting that the external system is not really reduced into an equivalent in this case, but rather, the goal becomes to determine how far the state estimation has to be solved for.

The IEEE-118 bus system is used in this section as well, and the configuration of the system is as shown in Figure 7, where the internal system is denoted as Area 1 and the external system as Area 2.

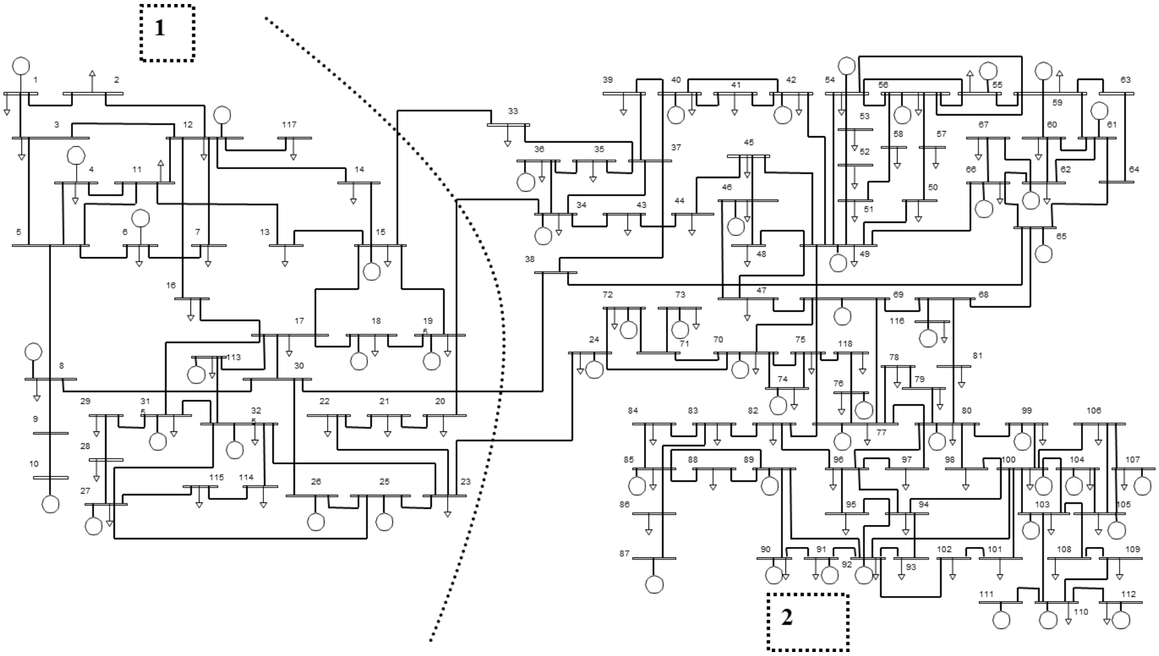

Figure 7. IEEE-118 bus system

In a power system network, the distance can often be referred to as either the electrical distance, or the minimum number of nodes connecting two points. Since the idea here is to create layers based on the distance from the internal system, these two concepts will be considered. One way is to create the layers based on the electrical distance from the internal system, and layers can be created based on different increments of electrical distance from the internal system.

A simpler way to create the layers is just to count the number of connecting nodes the buses are away from the internal system. In this dissertation, the system will be divided into layers based on the number of nodes for simplicity. The process for dividing the external system into layers is outlined in the ensuing section.

5.2. Dividing external system into layers

The IEEE-118 bus system is already illustrated above with Area 1 denoted as the internal system and Area 2 denoted as the external system. A script is written to divide the external system into layers, and the method in which this is done is shown below.

1. All buses in the internal system (Area 1) are labeled "Layer 1" buses. A search is performed to locate all buses in the external system (Area 2) which are also immediate neighbors of "Layer 1" buses. These buses will be labeled "Layer 2" buses. This is shown in Figure 8 where the red lines represent the "Layer 2" buses and also the lines connecting "Layer 1" and "Layer 2" buses.
2. In general, a search is performed to locate all buses in the external system (Area 2) which don't belong to any layer yet, and are also immediate neighbors of "Layer *i*" buses. These buses are labeled as "Layer (*i*+1)".
3. After all buses in the external system (Area 2) have been labeled, the division of the external system into layers is complete.

A step-by-step illustration of the creation of each layer of the external system for the IEEE-118 bus system in Figure 7 is shown below in Figure 8 to Figure 17. Each new layer is shown with a different color so the reader can understand clearly how the new layers are created.

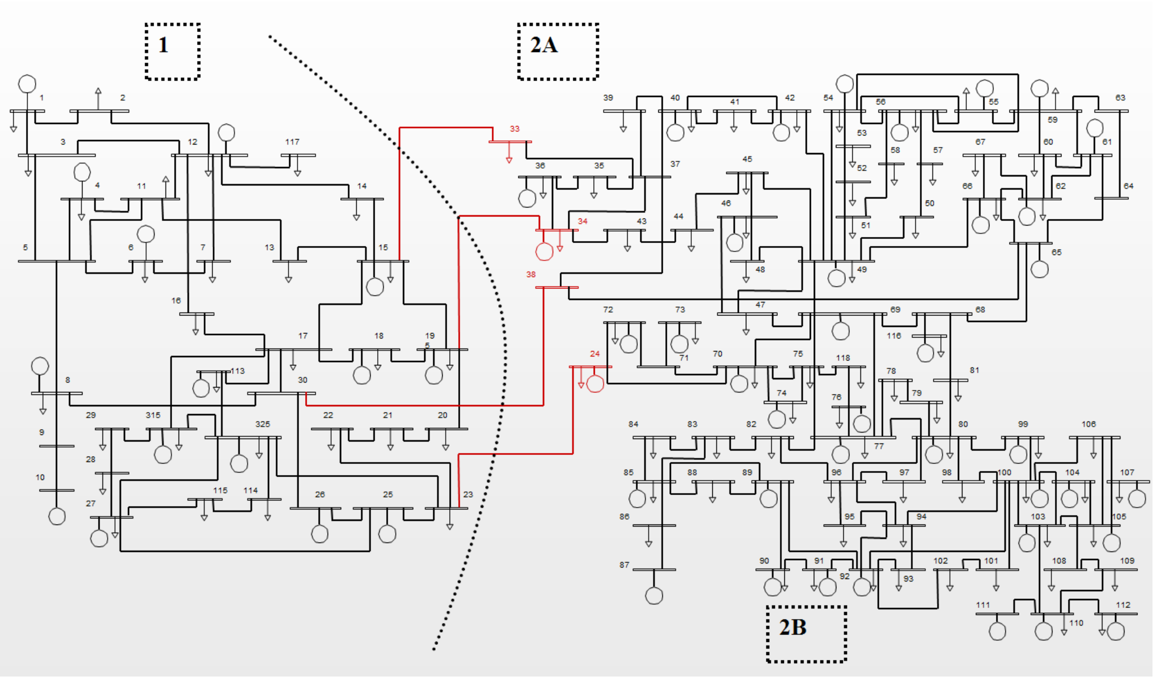

Figure 8. 118 bus system with external system extended to layer 2 (in color)

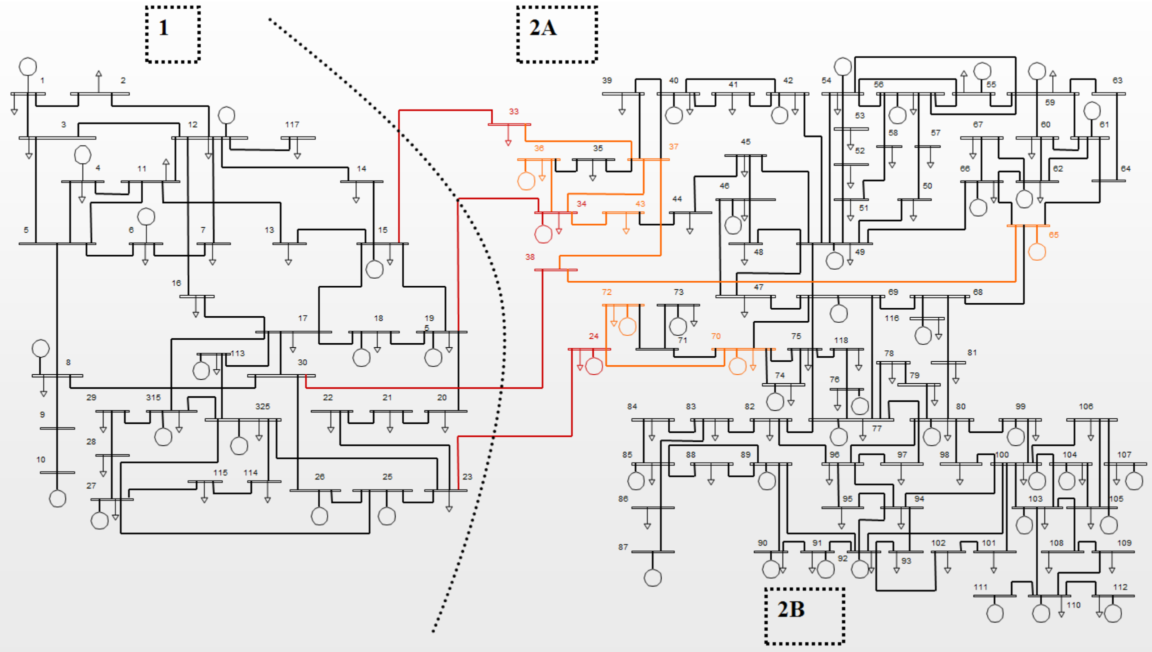

Figure 9. 118 bus system with external system extended to layer 3 (in color)

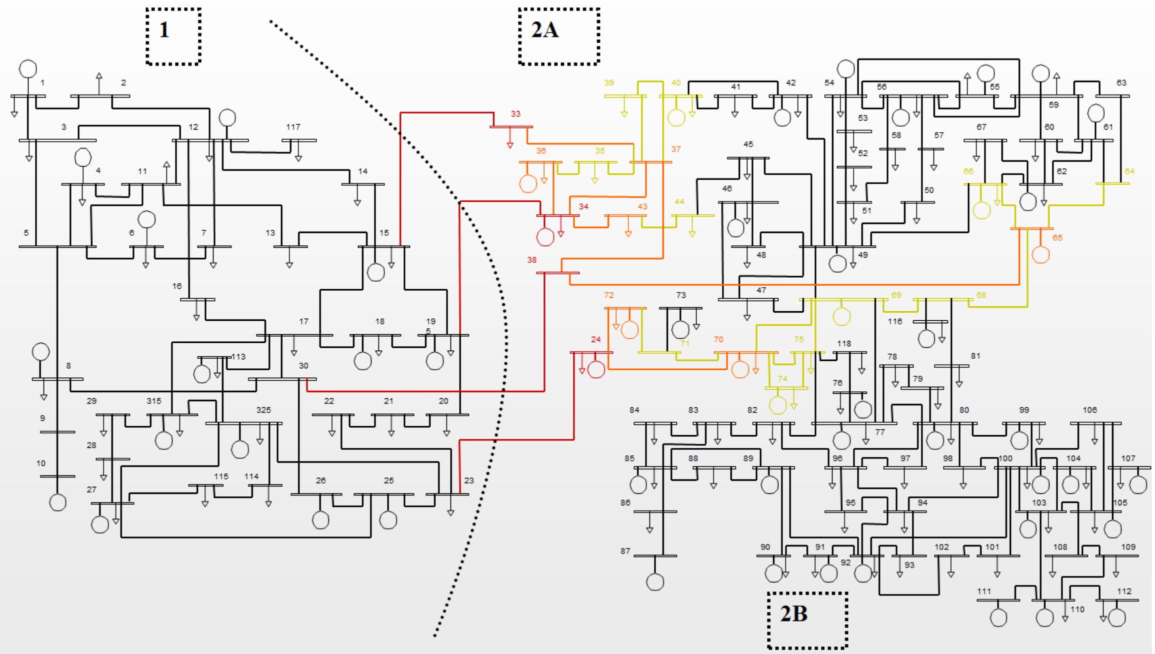

Figure 10. 118 bus system with external system extended to layer 4 (in color)

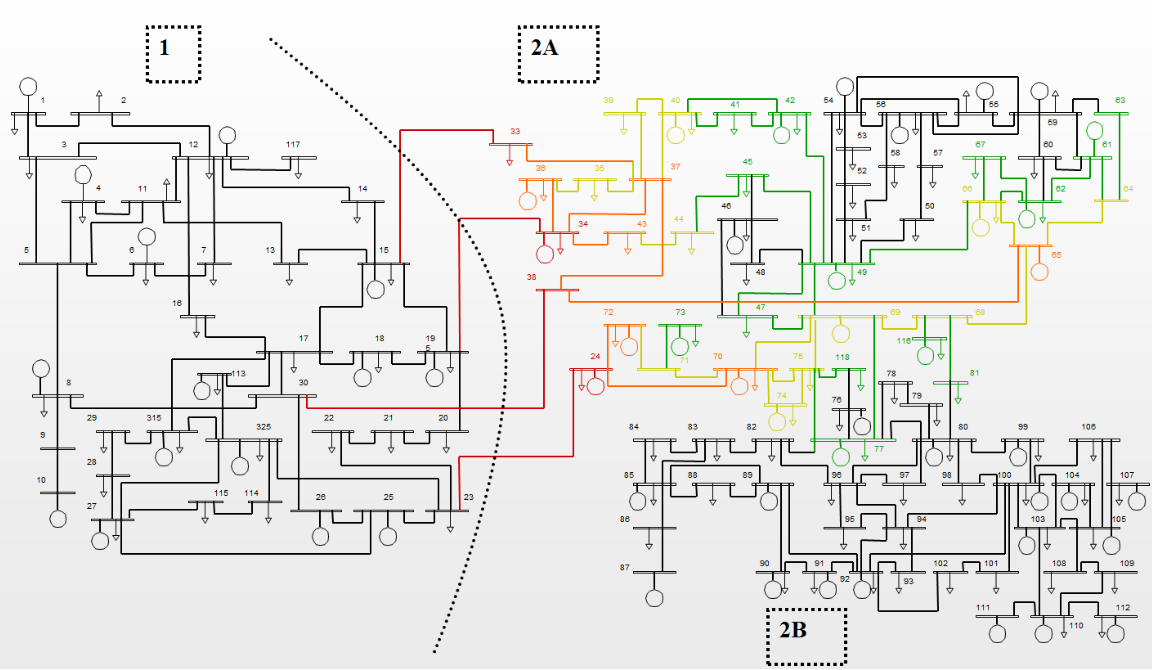

Figure 11. 118 bus system with external system extended to layer 5 (in color)

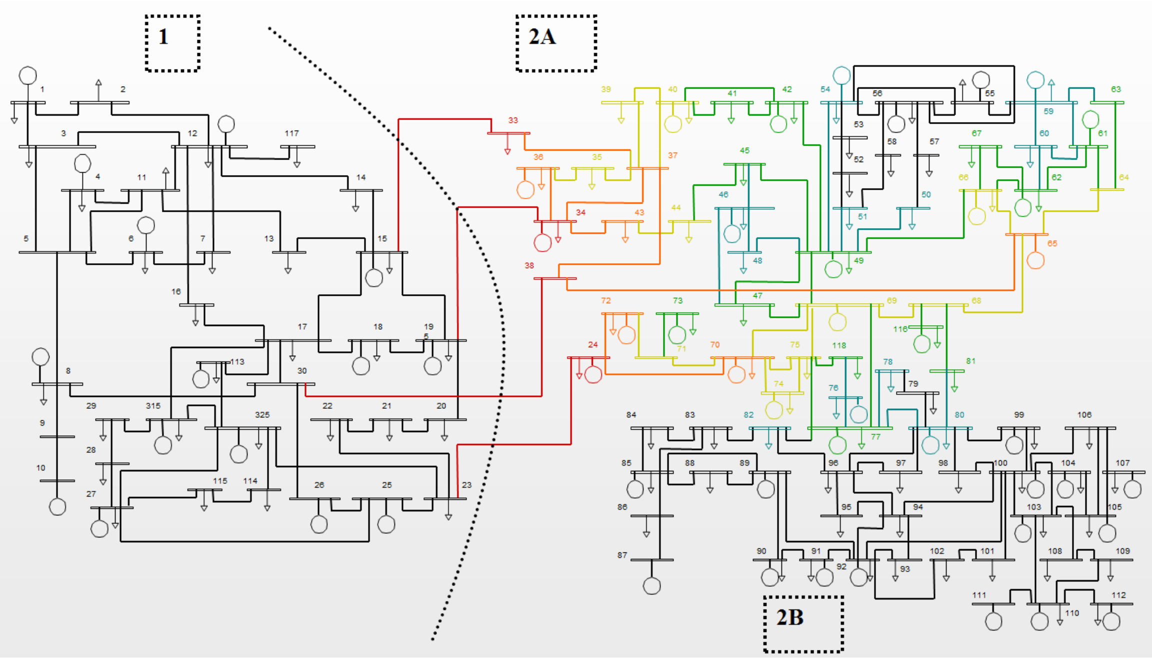

Figure 12. 118 bus system with external system extended to layer 6 (in color)

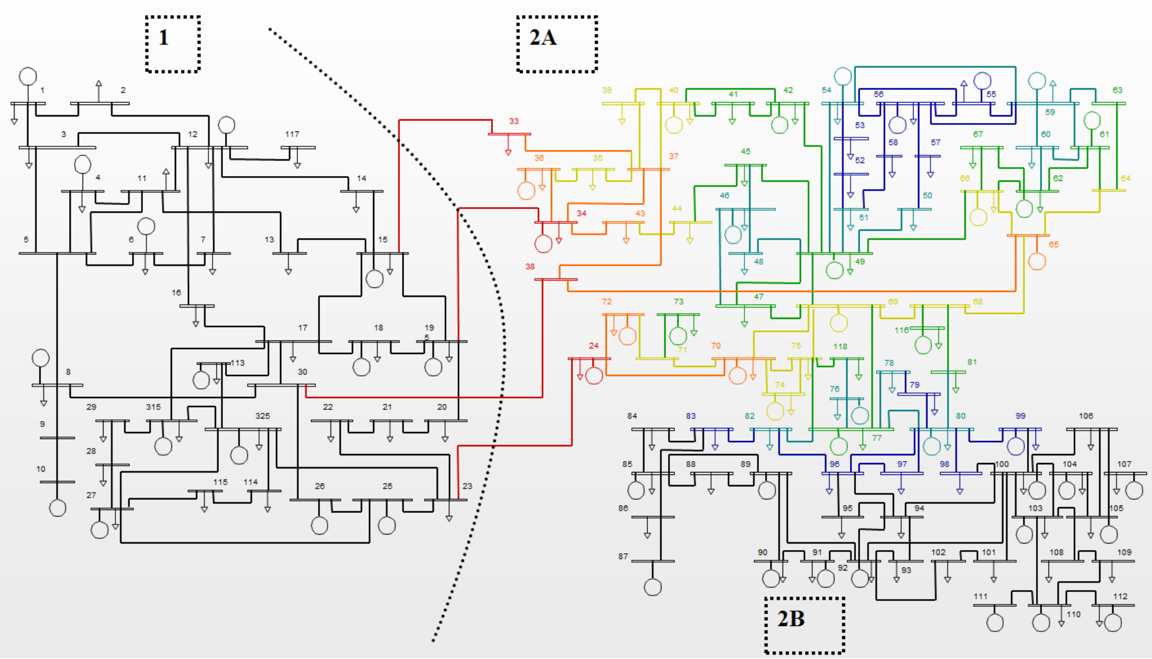

Figure 13. 118 bus system with external system extended to layer 7 (in color)

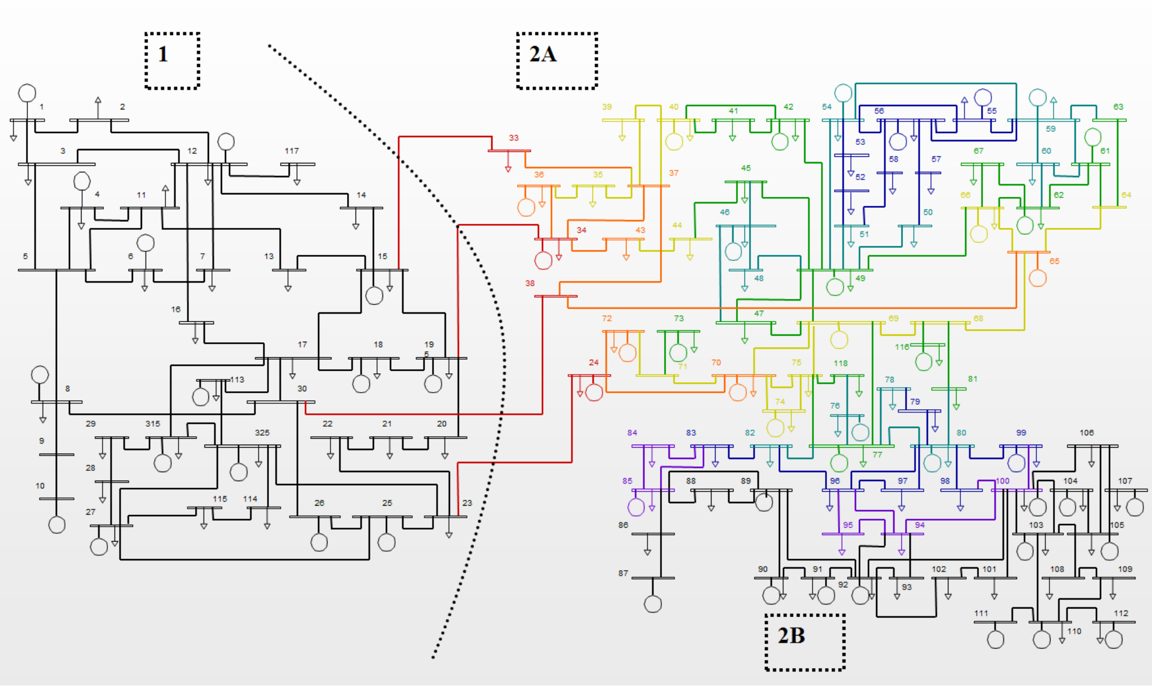

Figure 14. 118 bus system with external system extended to layer 8 (in color)

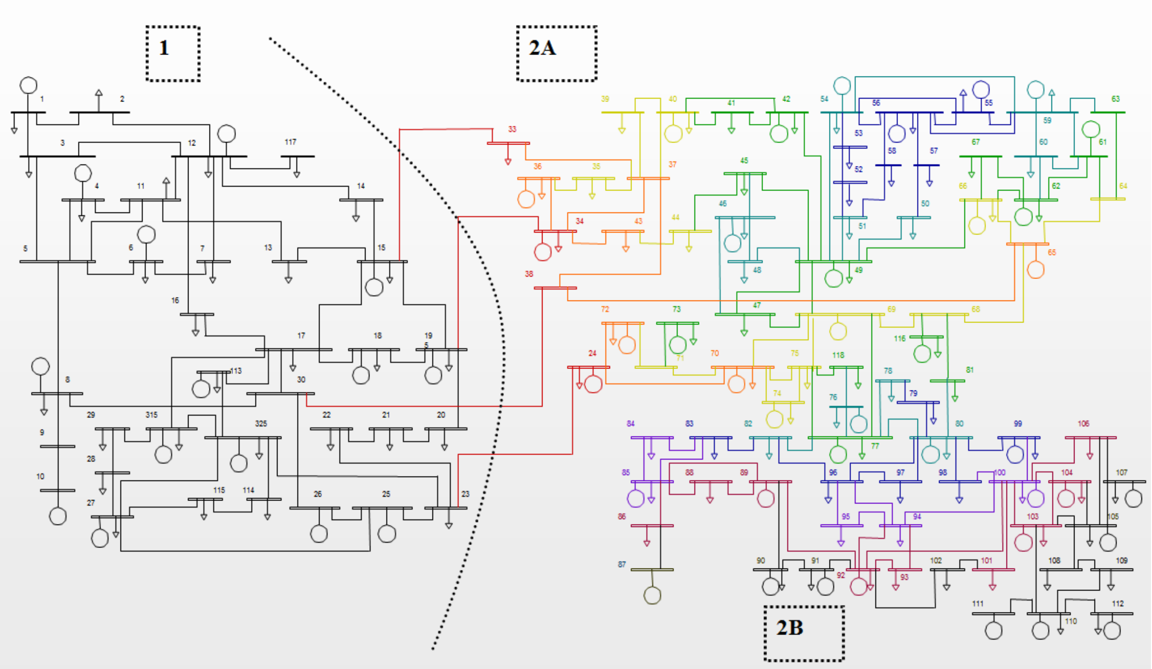

Figure 15. 118 bus system with external system extended to layer 9 (in color)

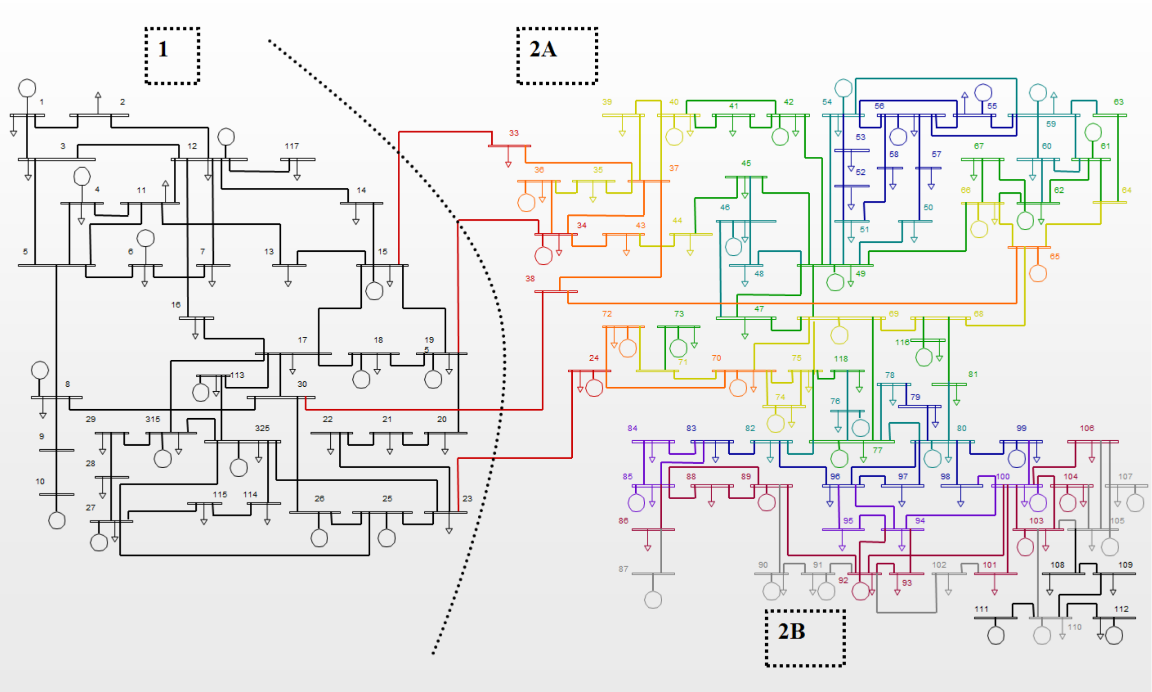

Figure 16. 118 bus system with external system extended to layer 10 (in color)

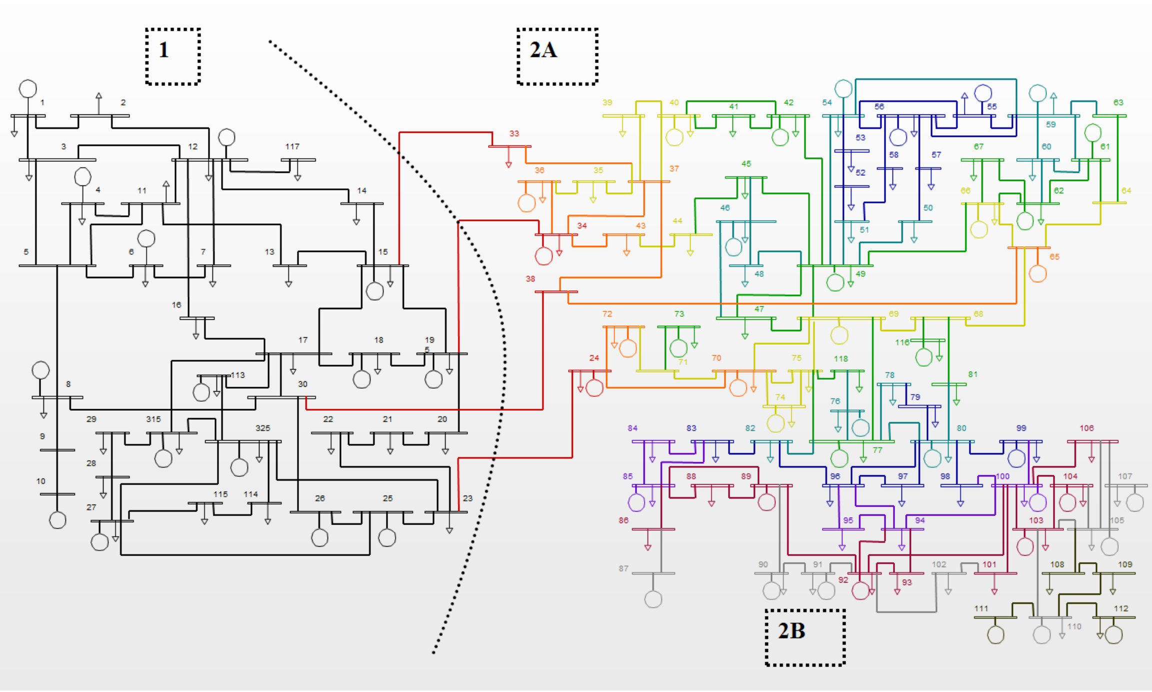

Figure 17. 118 bus system with external system extended to layer 11 (in color)

For the IEEE-118 bus system in Figure 7, it can be seen that the external system can be divided into 10 additional layers.

5.3. State Estimation with different amounts of external model

In this section, the effects of solving the state estimator to certain layers of the external model are investigated. It is worth noting that the external system model is not reduced in this section, but rather, adjustments are made so that the internal state estimator only solves up to certain layers of the external system.

Recall that the buses which are immediate neighbors of the internal system are denoted as Layer 2 buses. Note that these buses can also be defined as the external boundary buses. Without loss of generality, the process for solving the state estimator up to the i^{th} layer will now be described.

1. All buses in the internal system and external buses from the 1st layer to the i^{th} layer are retained. All tie lines connecting these retained buses are also retained.
2. Tie lines connecting buses in layer i to buses in layer (i+1) are then noted. Consider Figure 18 below, which shows part of a system, where the layer i bus is connected to other buses in layers (i-1), i or (i+1). Note that lines connected to the other buses are not shown here for simplicity. The real and reactive power flows which are noted down are $P_{ij,2}+Q_{ij,2}$ and $P_{ij,1}$ and $Q_{ij,1}$.
3. The real and reactive power flows on the tie lines noted in step 2 are converted into real and reactive power injections at the corresponding buses in layer i and these new real and reactive power injections at buses in layer i are then lumped together with the original real and reactive power injections

already at these buses. Note that the original real and reactive power injections at the layer *i* bus would be $P_{inj,init}=P_{G0}-P_{L0}$ while $Q_{inj,init}=Q_{G0}-Q_{L0}$. The new power injections would be $P_{inj,up}=P_{inj,init}-P_{ij,1}-P_{ij,2}$ while $Q_{inj,up}=Q_{inj,init}-Q_{ij,1}-Q_{ij,2}$ and the topology would appear as the one in Figure 19 below. Note that all the quantities above are the measurements obtained from SCADA data exchange.

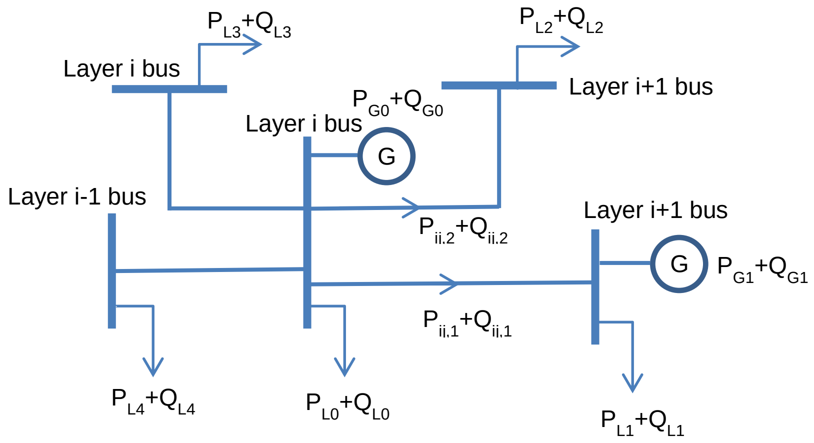

Figure 18. A portion of the system depicting a bus in layer *i* and its connecting buses

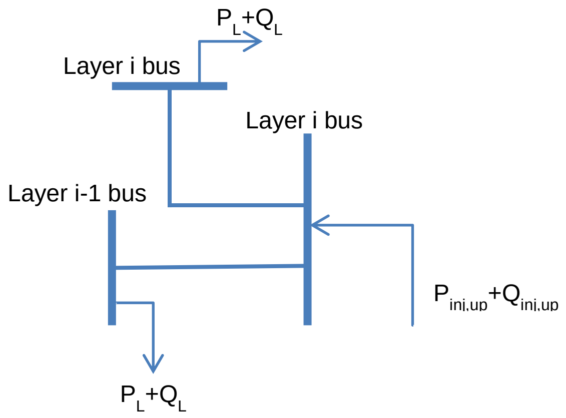

Figure 19. The schematics at the layer *i* bus from Figure 18 after adjustments

It was shown above that 11 layers are obtained for the IEEE-118 bus system, and hence, we will have 11 different systems for which state estimation can be solved. In general, system *i* would comprise buses which are in layer 1 up to layer *i*. Obviously, system 1 represents only the internal system buses. The process for solving each of these 11 systems is already provided above.

In the study comparing the effects of using solving different amounts of the external system during state estimation, the following metric will be used.

$$J_{118} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\overrightarrow{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\overrightarrow{V_i} - \overrightarrow{V_i^{PF}}\right)^*\right] \qquad (5\text{-}1)$$

where $\overrightarrow{V_i}$ is the estimated complex voltage at bus *i*

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the power flow solution

N is the number of internal system buses

Note that this metric is the same as ones used in previous studies and is provided here for the convenience of the reader. As in previous studies, a list of cases is created where there is a single topology change (line outage) in the external system, and simulations are run for different levels of data exchange corresponding to each scenario. The focus of this part is on determining how much of the external model is required to ensure accurate state estimation, and hence it is assumed that SCADA data exchange performed. In the exchange of SCADA data exchange, two scenarios are considered, one where the data exchanged is perfect, and another where there is a topology error in the external system's topology processor. In the latter case, this would mean that the SCADA data obtained from the external system would indicate the base case topology even when there is a line outage in the external system.

TABLE XXIX. State estimation accuracy metric (State estimator solved for different amounts of the IEEE-118 bus system)

System i	J_{118}(Mean) for all cases
1	2.17×10^{-6}
2	2.12×10^{-6}
3	1.39×10^{-5}
4	7.75×10^{-6}
5	7.51×10^{-6}
6	5.16×10^{-6}
7	1.82×10^{-6}
8	1.74×10^{-6}
9	1.79×10^{-6}
10	1.63×10^{-6}
11	1.78×10^{-6}

TABLE XXX. State estimation accuracy metric (State estimator solved for different amounts of the IEEE-118 bus system with errors in the external system topology processor)

System i	J_{118}(Mean) for all cases
1	2.36×10^{-6}
2	2.31×10^{-6}
3	4.61×10^{-5}
4	5.30×10^{-5}
5	5.80×10^{-5}
6	4.76×10^{-5}
7	4.27×10^{-5}
8	4.05×10^{-5}
9	3.68×10^{-5}
10	3.60×10^{-5}
11	3.55×10^{-5}

First of all, it is noted that the amount of the external system which is solved for when SCADA data exchange is implemented without any topology error from the external system does not really affect the state estimation results, and the state estimation accuracy metrics are all fairly small for all 11 systems in TABLE XXIX.

It can be then observed from TABLE XXX that the state estimation accuracy metric has higher values when there is a topology error in the external system's control center. This increase is not very obvious for the systems 1, 2 and 3, which represent the systems including very few layers of the external system. For the higher numbered systems, which represent more and more layers of the external system included during state estimation, the increase in the state estimation accuracy metric is by an order. Note that the accuracy metric value shown here is the mean of all the cases performed, meaning that the topology errors can be in different layers. It is believed that there is not much difference in the state estimation accuracy metrics for the lower numbered systems because they may not be solving the system up to the location where the topology errors are present. This will be further discussed in the next section.

5.4. Algorithm to determine proximity of topology error

In the previous section, it was noted that larger errors can appear in internal state estimation when inaccurate topology data is used in the system model for internal state estimation. In this section, an algorithm is proposed to help locate the proximity of the topology error. The focus in this chapter is to investigate how much of the external system is required for accurate internal state estimation and ensuing functions such as contingency analysis, and hence, the goal here is not to determine the exact location of the topology error. Instead, the goal of the proposed algorithm just helps determine how far an existing topology error is from the internal system.

From the previous subsection, it was noted that the number of layers of the external system which were included in the state estimation had little effect on the accuracy of internal system state estimation as long as the real-time analog and topology data is correct. The results in TABLE XXIX illustrated how the state estimation results were highly accurate regardless of how much of the external system was solved for. However, in the event where the SCADA data had topology errors in it, the state estimation accuracy metric value increased for cases where the topology change caused sufficiently large changes in the system operating conditions.

The idea behind this algorithm to locate the proximity of external topology errors lies in the assumption that topology errors will indeed lead to larger errors in internal state estimation if the topology change which is being neglected produces a sufficiently large change in the system operating conditions. Such errors would then be noted in the state estimation accuracy metric which is listed below again for the convenience of the reader.

$$J_{118} = \frac{1}{N}\sum_{i=1}^{N}\left[\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^{*}\right] \qquad \text{(5-2) or (5-1)}$$

where $\vec{V_i}$ is the estimated complex voltage at bus *i*

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the power flow solution

N is the number of internal system buses

The key lies in that when different systems with different amount of layers of the external system are solved for, some will be affected by the topology error, while others will not be affected by the topology error. Consider a topology error in the (i+1)th layer on line m-n. When the system is solved up to the i^{th} layer, the tie lines connecting buses in the i^{th} and $(i+1)^{th}$ layer will already have been converted to equivalent real and reactive power injections for corresponding buses in the i^{th} layer. Hence, when the analog measurements received from the external system are correct, the topology error no longer affects the internal state estimation process regardless of whether it is known or not. In the event that the topology error was on a line connecting a bus in the i^{th} layer and another bus in the $(i+1)^{th}$ layer, there would be a zero flow measurement for this line even if it is assumed to be in service. This would lead to correct adjustment of the real and reactive power injections at the corresponding bus in the i^{th} layer anyways. This is because the analog measurements are assumed to be correct during SCADA exchange and it is only the topology processor of the external system which is malfunctioning, which is the cause of a line outage not being seen. Hence, when solving up to the i^{th} layer only, such a topology change would have no effect on the internal state estimation accuracy regardless of whether it is known or not by the internal state estimator.

In the event that the internal state estimator solves for the external system up to the $(i+1)^{th}$ layer, the corresponding power and reactive power injection adjustments would be performed for buses in the $(i+1)^{th}$ layer which are connected to the $(i+2)^{th}$ layer, but the system topology used would assume that line m-n is still in service even though it is not because this line is now in the system which has to be solved for.

Intuitively, there would be a sudden increase in the state estimation accuracy metric when comparing the results for solving up to the $(i+1)^{th}$ layer with those where state estimation is solved up to the i^{th} layer. Obviously, another assumption is that the topology change on line m-n causes the system operating conditions to deviate sufficiently from the base case.

The algorithm to determine the proximity of a topology error in the external system is as follows.

1. Solve state estimation for all systems with different amount of layers
2. Determine the difference in the state estimation metric between consecutive layers. There are two methods in which this difference can be calculated.
    a. $\left|J^{i+1}-J^{i}\right|$ for i=1,…,n_layer-1; denote $max\left|J^{i+1}-J^{i}\right|$ as $|J^{m1+1}-J^{m1}|$. This method just calculates the difference in the state estimation metric between 2 layers, and finds where the maximum difference occurs.
    b. $\left|J^{i+1}/J^{i}\right|$ for i=1,…,n_layer-1; denote $max\left|J^{i+1}/J^{i}\right|$ as $|J^{m2+1}/J^{m2}|$, calculate $|J^{m2+1}|$. This method determines where the largest jump in state estimation metric between 2 layers occurs, and also tracks down the value of the state estimation accuracy metric in the layer where the jump occurs.
3. Locate layer in which topology change is associated with
    a. $|J^{m1+1}-J^{m1}|$ indicates that the largest increase in the state estimation metric as an additional layer of the external system is solved for during state estimation occurs when layer (m1+1) is solved. According to the concept behind which this algorithm is created, this

means that the topology change is either between a bus in the m1th and (m1+1)th layer, or between 2 buses which are both in the (m1+1)th layer.

b. $|J^{m2+1}|$ indicates that the largest increase in the state estimation metric as an additional layer of the external system is solved for during state estimation occurs when layer (m2+1) is solved. This index implies that the topology change is either between a bus in the m2th and (m2+1)th layer, or between 2 buses which are both in the (m2+1)th layer.

As mentioned before, one of the assumptions in the algorithm is that the topology change on line m-n causes the system operating conditions to change sufficiently from the base case. In cases where the system operating conditions do not change much, the state estimation results would be fairly accurate regardless of whether the topology change is known or not, since the topology change does not affect the system much. Therefore, this algorithm can only be used on cases where the state estimation results actually deteriorate when the topology error exists. A threshold is put on the minimum values of indices $|J^{m1+1} - J^{m1}|$ and $|J^{m2+1}|$ so that only the significant cases will be considered for by this algorithm. This threshold value is set to be 1 x 10^{-4} in the experiment, and the results are shown in TABLE XXXI below.

TABLE XXXI. RESULTS OF ALGORITHM FOR LOCATING PROXIMITY OF TOPOLOGY ERROR

			Method 1			Method 2		
Topology change		Associated Layers	$\lvert J^{m1+1}-J^{m1}\rvert$	m1	m1+1	$\lvert J^{m2+1}\rvert$	m2	m2+1
30	38	1-2	1.80×10^{-4}	3	4	1.40×10^{-4}	1	2
38	37	2-3	3.56×10^{-4}	4	5	3.29×10^{-4}	2	3
38	65	2-3	5.71×10^{-4}	2	3	5.71×10^{-4}	2	3
42	49	5-5	4.78×10^{-4}	4	5	4.97×10^{-4}	4	5
49	66	5-4	3.35×10^{-4}	4	5	3.74×10^{-4}	4	5
63	59	5-6	1.97×10^{-4}	5	6	2.05×10^{-4}	5	6
63	64	5-4	1.85×10^{-4}	5	6	1.99×10^{-4}	5	6
64	65	4-3	3.47×10^{-4}	3	4	3.57×10^{-4}	3	4
65	68	3-4	7.85×10^{-4}	3	4	8.53×10^{-4}	3	4
66	67	4-5	1.64×10^{-4}	4	5	1.83×10^{-4}	4	5
68	69	4-4	4.40×10^{-4}	3	4	4.46×10^{-4}	3	4
68	81	4-5	1.16×10^{-4}	4	5	1.17×10^{-4}	4	5
68	116	4-5	4.18×10^{-4}	3	4	4.30×10^{-4}	3	4
69	70	4-3	5.83×10^{-4}	3	4	5.94×10^{-4}	3	4
69	75	4-4	4.02×10^{-4}	3	4	4.11×10^{-4}	3	4
70	71	3-4	1.70×10^{-4}	3	4	1.81×10^{-4}	3	4
81	80	5-6	2.10×10^{-4}	8	9	1.68×10^{-4}	5	6

TABLE XXXI illustrates the list of external topology changes which have been screened by the algorithm. These topology changes have all been shown to produce sufficient changes to the system operating conditions and are thus adopted for testing of the algorithm. The column "Associated Layers", which is in the form *i*-*j* illustrates that the topology change occurs between a bus in layer *i* and a bus in layer *j*. The indices $|J^{m1+1} - J^{m1}|$ and $|J^{m2+1}|$ are shown, and the columns on the right of the corresponding indices describe the location where the algorithm believes the error to be.

For Method 1, the algorithm does not always provide an accurate prediction of where the topology change has occurred and is accurate in 12 of the 17 cases. In cases where it provides an inaccurate prediction, it tends to determine that the topology change is further away from the internal system than it actually is.

For Method 2, the algorithm successfully determines how far the topology change is for all 17 cases. For the topology changes on lines 42-49, 68-69 and 69-75 which are associated with layers 5-5, 4-4 and 4-4 respectively, the results in the table for Method 2 indicate layers 4-5, 3-4 and 3-4 respectively. As mentioned during the description of the algorithm itself, this illustration is correct, as the value of (m2+1) indicates that the topology change is either between a bus in the m2th and (m2+1)th layer, or between 2 buses which are both in the (m2+1)th layer. The value m2 is illustrated in TABLE XXXI only for the convenience of the reader, so that the approximate location of the topology change can be seen immediately without having to read back into the algorithm description.

It has been shown that this algorithm can be successfully used to determine the approximate location of an unknown topology change once the threshold is set correctly to only account for cases where the system operating conditions have changed sufficiently after a topology change. This will provide control centers an idea of how much of the external model can still be used to provide accurate state estimation results.

One may argue that the algorithm may not work when the real solution of the system state is unknown. However, from the previous section, it is already shown that the amount of the external system which is solved for does not affect the state estimation results when the measurements exchanged are correct and when the topology knowledge is correct. System 1, which includes the internal system only would therefore be able to generate state estimation results which are correct as long as the measurements obtained from the internal system's SCADA system are correct. Moreover, since the buses in layer 2 are tied to the boundary buses of the internal system, and their topology is always known, except in the event of a topology error in the internal system's control center, which is out of the scope of the goals of this algorithm. Hence, the metric J_{118} can be recalculated with the solution from solving only the internal system with modifications at the tielines with external system being adopted as the actual solution, and the algorithm would still be able to work properly.

5.5. Contingency Analysis

5.5.1. Effects of different levels of data exchange on contingency analysis

In the previous sections, it was noted that the amount of the external system which is solved for has little to no effects on internal state estimation accuracy as long as the data exchanged is correct and up to date. This was as expected, since the amount of the external model which is used is more critical for subsequent EMS functions such as contingency analysis. In this section, the effects of data exchange during internal state estimation on ensuing contingency analysis will be studied.

The approach for performing contingency analysis studies is as follows:

1. Solve state estimator for a specified case. The measurements and topology data to be used will depend on the scenario, which will be described in corresponding parts of the dissertation.
2. Contingency analysis is run based on the state estimator solution from step 1. All n-1 lines contingencies are taken into account for the contingency analysis.

3. The contingency analysis solutions are then compared with the exact solutions which will be known since the IEEE-118 test bed system is being investigated. The contingency analysis accuracy metric is shown below.

$$J_{cont,118} = \frac{1}{N}\sum_{i=1}^{N}\left[\sqrt{\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^*}\right] \qquad (5\text{-}3)$$

where $\vec{V_i}$ is the complex voltage at bus *i* from contingency analysis

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the exact power flow solution

N is the number of internal system buses

In previous sections, it was noted that not all topology changes in the external system for Configuration 2 of the IEEE-118 bus system lead to substantial changes in the system operating conditions. In this section, only lines which would lead to sufficient changes in the system operating conditions will be considered for external outages. The following lines are considered for external outages – 34-37, 38-65, 42-49, 49-66, 60-61, 63-64, 64-65, 69-70, 77-80, 88-89, 89-90, 89-92 and 100-103. Each line outage will constitute a case to be studied in contingency analysis.

The different scenarios to be created for the study of the effects of data exchange during internal state estimation on contingency analysis are described below. The first scenario (5A) will represent a situation where there is no data exchange with the external system during internal state estimation. Pseudo measurements based on the base case will be used for the external system to ensure observability, and there will be no knowledge of the corresponding topology change in the case.

The second scenario (5B) will represent a situation where SCADA data exchange is performed, so that the analog data and topology data are both up to date and correct during internal state estimation.

The third scenario (5C) will be one where SCADA data is exchanged with the external system, but the external system will have errors in its topology processor, and the topology change corresponding to the case being studied will not be seen. Hence, the internal system will have up to date analog measurements during state estimation, but the system topology used will be incorrect. The scenarios are summarized in TABLE XXXII below.

TABLE XXXII. Scenarios for investigation of effects of data exchange during state estimation on ensuing contingency analysis (Testbed system: IEEE-118 bus system in Figure 7)

Scenario	Description
5A	Contingency analysis for the case where the state estimation solution is from a situation where no data exchange with the external system. Pseudo measurements were made for the external system to ensure system observability
5B	Contingency analysis for the case where the state estimation solution is from a situation where SCADA data exchange is performed with the external system.
5C	Contingency analysis for the case where the state estimation solution is from a situation where SCADA data exchange is performed with the external system, but the external system's topology processor is malfunctioning. Topology changes in the external systems remain unknown to the internal system

The mean values of the contingency analysis accuracy metric are shown in TABLE XXXIII below. From the tables, it can be seen that the contingency analysis is very accurate in Scenario 5B. This is reasonable, since the state estimation solutions are obtained after perfect data exchange was implemented with the external system, and so, the state estimation solutions should have been highly accurate and reflective of the system exact solution. For scenario 5C, the contingency analysis performance appears to be worse when certain topology changes are unknown, which is also reasonable, since the state estimation solutions from which the contingency analysis is based on may not be very accurate as a result of the incorrect topology knowledge when it is solved. An interesting point to note is that it appears that Scenario 5A provides better contingency analysis performance than Scenario 5C despite the fact that there was no data exchange during the state estimation for that Scenario. This may have been a result of the fact that when no data exchange is performed, the pseudo measurements have a lower weight than the actual measurements of the internal system. However, in Scenario 5C, all measurements have the same weight during state estimation since the internal system assumes that all real-time data received is correct.

TABLE XXXIII. Contingency analysis accuracy metric for Scenarios 5A, 5B and 5C (Testbed system: IEEE-118 bus system in Figure 7)

	$J_{cont,118}$(Mean) for all n-1 contingencies		
Case (External topology change on line m_n)	Scenario 5A	Scenario 5B	Scenario 5C
34_37	3.39×10^{-4}	2.08×10^{-4}	4.37×10^{-3}
38_65	1.69×10^{-3}	4.02×10^{-4}	3.44×10^{-3}
42_49	2.29×10^{-4}	1.82×10^{-4}	9.32×10^{-4}
49_66	2.75×10^{-4}	1.66×10^{-4}	1.28×10^{-2}
60_61	2.78×10^{-4}	1.90×10^{-4}	2.15×10^{-4}
63_64	3.47×10^{-4}	2.19×10^{-4}	4.11×10^{-3}
64_65	3.82×10^{-4}	3.86×10^{-4}	2.49×10^{-3}
69_70	1.36×10^{-3}	4.22×10^{-4}	2.59×10^{-3}
77_80	6.06×10^{-4}	3.80×10^{-4}	5.59×10^{-4}
88_89	3.33×10^{-4}	1.85×10^{-4}	2.69×10^{-4}
89_90	2.52×10^{-4}	2.86×10^{-4}	4.91×10^{-4}
89_92	2.51×10^{-4}	3.56×10^{-4}	7.94×10^{-3}
100_103	1.99×10^{-4}	2.03×10^{-4}	6.65×10^{-4}

The contingency analysis accuracy metrics do not show very clearly the differences in contingency performance result, so the mean errors at the boundary buses are also observed and are shown in TABLE XXXIV.

TABLE XXXIV. Mean boundary bus errors for Scenarios 5A, 5B and 5C (Testbed system: IEEE-118 bus system in Figure 7)

	Mean of boundary bus absolute errors		
Case (External topology change on line m_n)	Scenario 5A	Scenario 5B	Scenario 5C
34_37	8.90×10^{-3}	1.48×10^{-3}	2.95×10^{-2}
38_65	2.28×10^{-2}	2.34×10^{-3}	2.78×10^{-2}
42_49	6.78×10^{-3}	1.27×10^{-3}	8.42×10^{-3}
49_66	3.42×10^{-3}	8.13×10^{-3}	9.23×10^{-2}
60_61	1.86×10^{-3}	9.28×10^{-4}	1.15×10^{-3}
63_64	2.09×10^{-3}	1.33×10^{-3}	2.93×10^{-2}
64_65	1.76×10^{-3}	1.93×10^{-3}	1.68×10^{-2}
69_70	8.44×10^{-3}	2.40×10^{-3}	1.75×10^{-2}
77_80	3.54×10^{-3}	1.99×10^{-3}	3.48×10^{-3}
88_89	1.94×10^{-3}	8.91×10^{-4}	1.36×10^{-3}
89_90	1.80×10^{-3}	1.94×10^{-3}	3.82×10^{-3}
89_92	1.11×10^{-3}	1.86×10^{-3}	5.79×10^{-2}
100_103	1.57×10^{-3}	1.31×10^{-3}	4.46×10^{-3}

Similar trends can be observed from the mean boundary bus errors. To gain deeper insight in the effects of data exchange during state estimation on contingency analysis performance, the data for each contingency is perused and some contingency cases of interest are noted.

TABLE XXXV shows the results for contingency analysis on line 26-30 in the internal system. Several cases are noted. The first case represents a line outage on line 34-37 in the external system. During state estimation, the line outage is unknown for Scenarios 5A and 5C, whereas it is known during 5B. The contingency analysis results show that both Scenarios 5A and 5C show relatively large errors at the boundary buses, whereas the boundary bus errors for Scenario 5B are very small, indicating very accurate contingency analysis results.

Similar observations are noted for external topology changes on lines 38-65, 42-49 and 69-70 respectively.

TABLE XXXV. Mean boundary bus errors for Scenarios 5A, 5B and 5C (Testbed system: IEEE-118 bus system in Figure 7, Specific contingency case)

Contingency case	26_30		
		Mean of boundary bus errors	
External topology change	Scenario 5A	Scenario 5B	Scenario 5C
34_37	1.16×10^{-2}	3.54×10^{-3}	8.27×10^{-2}
38_65	2.54×10^{-2}	6.24×10^{-3}	2.54×10^{-2}
42_49	9.08×10^{-3}	2.71×10^{-3}	1.23×10^{-2}
69_70	2.34×10^{-2}	5.65×10^{-3}	4.78×10^{-2}

TABLE XXXVI shows the contingency analysis results for line 26-25 in the internal system. Once again, several cases are of interest. The most notable one is for a line outage on line 38-65 in the external system. During state estimation, the line outage is unknown for Scenarios 5A and 5C, whereas it is known during 5B. The contingency analysis results show that both Scenarios 5A and 5C show fairly large errors at the boundary buses, whereas the boundary bus errors for Scenario 5B are very small, indicating very accurate contingency analysis results. Similar trends are noted for external topology changes on lines 42-49 and 69-70.

TABLE XXXVI. Mean boundary bus errors for Scenarios 5A, 5B and 5C (Testbed system: IEEE-118 bus system in Figure 7, Specific contingency case)

Contingency case	26_25		
		Mean of boundary bus errors	
External topology change	Scenario 5A	Scenario 5B	Scenario 5C
38_65	4.52×10^{-2}	2.62×10^{-3}	5.88×10^{-2}
42_49	6.90×10^{-3}	1.71×10^{-3}	1.49×10^{-2}
69_70	1.02×10^{-2}	3.98×10^{-3}	1.80×10^{-2}

In this section, the effects of different levels of data exchange during state estimation on the ensuing contingency analysis have been studied. It is noted that the contingency analysis accuracy metric does not show obviously large differences for these different levels of data exchange. However, fairly large errors can be noted at boundary buses during contingency analysis if no data is exchanged. An interesting point to note is that large errors can also be found at boundary buses even when SCADA data is exchanged during state estimation if the topology knowledge exchanged is incorrect. Once again, the importance of having correct topology data during state estimation is observed.

5.5.2. Effects of using different amounts of the external model on contingency analysis

In the previous section, the effects of different levels of data exchange during state estimation on ensuing contingency analysis were studied. In this section, the effects of the state estimator solving for different amounts of the external model on ensuing contingency analysis are studied.

The approach for performing contingency analysis studies for this section is as follows:

1. Solve state estimator up to a desired number of layers of the external system
2. Contingency analysis is run based on the state estimator solution from step 1 and the system model will only be included up to the corresponding layers of the external model for each state estimator solution obtained. All n-1 line contingencies are taken into account for contingency analysis
3. The contingency analysis solutions are then compared with the exact solutions since the IEEE-118 test bed system is being investigated. The contingency analysis accuracy metric is as shown below:

$$J_{cont} = \frac{1}{N}\sum_{i=1}^{N}\left[\sqrt{\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^*}\right] \qquad (5\text{-}4)$$

where $\vec{V_i}$ is the complex voltage at bus *i* from contingency analysis

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus *i* based on the exact power flow solution

N is the number of internal system buses

In the study of how much of the external model is needed for accurate contingency analysis results after obtaining the state estimation results, the base case is first considered. For the base case, the issue of levels of data exchange and no scenarios are created for comparison during the state estimation process in step 1. The reason for this is that there is no difference whether SCADA data is exchanged or not in the base case, as the pseudo measurements that would be used to illustrate no data exchange would be the same as the measurements that are exchanged during SCADA data exchange. Moreover, the need to consider the possibility of a topology error in the external system during SCADA data exchange is also eliminated, since there are no topology changes in the external system, and the base case topology is already correct. Once again, all n-1 contingencies in the internal system are investigated, and the results are shown in TABLE XXXVII below.

TABLE XXXVII. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system at base case operating conditions)

State Estimator solved up to:	J_{cont}(Mean) for all n-1 contingencies
Internal System	8.77×10^{-4}
Layer 2	8.53×10^{-4}
Layer 3	4.04×10^{-3}
Layer 4	1.01×10^{-2}
Layer 5	4.08×10^{-3}
Layer 6	9.00×10^{-3}
Layer 7	6.21×10^{-3}
Layer 8	3.77×10^{-3}
Layer 9	3.31×10^{-3}
Layer 10	2.60×10^{-4}
Layer 11	2.54×10^{-4}

From the results for the base case, it is not so obvious how the amount of external model used affects the accuracy of contingency analysis. It appears that using a larger portion of the external model provides more accurate contingency analysis results (Layer 10, 11), but the discrepancies in the contingency analysis accuracy metric are not large enough to be conclusive.

Next, the case is considered for when there is a line outage in the external system. Since the goal is to determine how much of the external system is needed for accurate contingency analysis, SCADA data exchange is assumed for all the cases. It is also of interest to see the effects of topology errors on contingency analysis, so another scenario is assumed where SCADA data exchange is implemented, but with the issue of topology errors in the external system. In this scenario, the internal system would not be aware of the external line outage incurred for each case during performing contingency analysis.

TABLE XXXVIII. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system for all external line outages)

Mean for all external outages		
	SCADA data exchange	SCADA data exchange with topology error
State Estimator solved up to:	J_{cont}(Mean) for all n-1 contingencies	J_{cont}(Mean) for all n-1 contingencies
Internal System	1.28×10^{-3}	1.28×10^{-3}
Layer 2	9.68×10^{-4}	9.68×10^{-4}
Layer 3	4.68×10^{-3}	4.68×10^{-3}
Layer 4	9.58×10^{-3}	9.99×10^{-3}
Layer 5	4.22×10^{-3}	5.47×10^{-3}
Layer 6	9.80×10^{-3}	1.15×10^{-2}
Layer 7	6.73×10^{-3}	9.32×10^{-3}
Layer 8	3.61×10^{-3}	6.06×10^{-3}
Layer 9	3.02×10^{-3}	5.93×10^{-3}
Layer 10	2.89×10^{-4}	3.38×10^{-3}
Layer 11	2.76×10^{-4}	3.37×10^{-3}

TABLE XXXVIII shows the results for the mean values of J_{cont} for all n-1 contingencies run on all external line outages listed before. From the table, it can be observed that using more of the external model provides more accurate contingency analysis results (Observe layers 10 and 11 for SCADA exchange). However, the value of the contingency analysis accuracy metric is not that large when smaller portions of the external system are used for contingency analysis either, so further investigation into individual cases will be performed.

Some cases of interest are shown below in TABLE XXXIX to TABLE XLIII. These cases illustrated are for an internal contingency on line 26-30 and external line outages on lines 34-37, 42-49, 49-66, 63-64 and 89-92 respectively. For these cases, it can be seen that the contingency analysis results are only accurate when the 10th or 11th system is solved for during state estimation. This shows that a large portion of the external mode is required for highly accurate state estimation results. Obviously, static equivalents have not been created at every layer of the system, but it is believed that this would not affect the results.

When smaller portions of the external model are used, the contingency analysis results are sometimes sufficiently erroneous even when SCADA data exchange without topology errors is implemented during the state estimation process. For these cases, the contingency analysis results are also erroneous when SCADA data exchange is implemented with topology errors during internal state estimation. In these cases, it is not obvious the effects of topology errors during state estimation have on ensuing contingency analysis.

When larger portions of the external model are used, the contingency analysis results are fairly accurate when SCADA data exchange is performed without topology errors during state estimation. For the same cases, but where there are topology errors during state estimation, it can be seen that the contingency analysis results will start to deteriorate. Once again, the importance of having correct topology knowledge during the state estimation process can be noted, and it can be seen that inaccuracy in state estimation results because of incorrect topology knowledge will be carried on to ensuing contingency analysis.

TABLE XXXIX. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system, specific case)

External line outage	34-37	
Internal contingency	26-30	
	SCADA data exchange	SCADA data exchange with topology error
State Estimator solved up to:	J_{cont}	J_{cont}
Internal System	1.47 x 10^{-2}	1.47 x 10^{-2}
Layer 2	1.37 x 10^{-2}	1.37 x 10^{-2}
Layer 3	3.35 x 10^{-2}	3.28 x 10^{-2}
Layer 4	5.63 x 10^{-2}	5.53 x 10^{-2}
Layer 5	2.82 x 10^{-2}	2.78 x 10^{-2}
Layer 6	2.94 x 10^{-2}	4.64 x 10^{-2}
Layer 7	2.04 x 10^{-2}	3.57 x 10^{-2}
Layer 8	1.24 x 10^{-2}	2.68 x 10^{-2}
Layer 9	1.03 x 10^{-2}	2.47 x 10^{-2}
Layer 10	6.21 x 10^{-4}	1.46 x 10^{-2}
Layer 11	5.61 x 10^{-4}	1.45 x 10^{-2}

TABLE XL. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system, specific case)

External line outage	42-49	
Internal contingency	26-30	
	SCADA data exchange	SCADA data exchange with topology error
State Estimator solved up to:	J_{cont}	J_{cont}
Internal System	1.86 x 10^{-2}	1.86 x 10^{-2}
Layer 2	1.49 x 10^{-2}	1.49 x 10^{-2}
Layer 3	4.02 x 10^{-2}	4.02 x 10^{-2}
Layer 4	4.63 x 10^{-2}	4.63 x 10^{-2}
Layer 5	1.24 x 10^{-2}	1.70 x 10^{-2}
Layer 6	2.99 x 10^{-2}	3.38 x 10^{-2}
Layer 7	2.01 x 10^{-2}	2.34 x 10^{-2}
Layer 8	1.21 x 10^{-2}	1.44 x 10^{-2}
Layer 9	1.01 x 10^{-2}	1.21 x 10^{-2}
Layer 10	4.69 x 10^{-4}	1.97 x 10^{-3}
Layer 11	4.14 x 10^{-4}	1.84 x 10^{-3}

TABLE XLI. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system, specific case)

External line outage	49-66	
Internal contingency	26-30	
	SCADA data exchange	SCADA data exchange with topology error
State Estimator solved up to:	J_{cont}	J_{cont}
Internal System	1.59 x 10^{-2}	1.59 x 10^{-2}
Layer 2	1.47 x 10^{-2}	1.47 x 10^{-2}
Layer 3	2.68 x 10^{-2}	2.68 x 10^{-2}
Layer 4	7.05 x 10^{-3}	7.05 x 10^{-3}
Layer 5	7.13 x 10^{-3}	2.97 x 10^{-2}
Layer 6	3.05 x 10^{-2}	6.56 x 10^{-2}
Layer 7	1.97 x 10^{-2}	7.30 x 10^{-2}
Layer 8	1.15 x 10^{-2}	6.06 x 10^{-2}
Layer 9	9.62 x 10^{-3}	5.77 x 10^{-2}
Layer 10	1.90 x 10^{-4}	4.37 x 10^{-2}
Layer 11	2.57 x 10^{-4}	4.35 x 10^{-2}

TABLE XLII. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system, specific case)

External line outage	63-64	
Internal contingency	26-30	
	SCADA data exchange	SCADA data exchange with topology error
State Estimator solved up to:	J_{cont}	J_{cont}
Internal System	1.53 x 10^{-2}	1.53 x 10^{-2}
Layer 2	1.43 x 10^{-2}	1.43 x 10^{-2}
Layer 3	2.44 x 10^{-2}	2.44 x 10^{-2}
Layer 4	3.22 x 10^{-2}	3.22 x 10^{-2}
Layer 5	1.23 x 10^{-2}	1.26 x 10^{-2}
Layer 6	3.76 x 10^{-2}	3.14 x 10^{-2}
Layer 7	1.91 x 10^{-2}	3.38 x 10^{-2}
Layer 8	1.16 x 10^{-2}	2.51 x 10^{-2}
Layer 9	1.01 x 10^{-2}	2.36 x 10^{-2}
Layer 10	2.15 x 10^{-4}	1.30 x 10^{-2}
Layer 11	2.22 x 10^{-4}	1.29 x 10^{-2}

TABLE XLIII. Contingency analysis accuracy metric (State estimation solved for different levels of the IEEE-118 bus system, specific case)

External line outage	89-92	
Internal contingency	26-30	
	SCADA data exchange	SCADA data exchange with topology error
State Estimator solved up to:	J_{cont}	J_{cont}
Internal System	1.76×10^{-2}	1.76×10^{-2}
Layer 2	1.61×10^{-2}	1.61×10^{-2}
Layer 3	2.65×10^{-2}	2.65×10^{-2}
Layer 4	1.80×10^{-2}	1.80×10^{-2}
Layer 5	6.54×10^{-3}	6.54×10^{-3}
Layer 6	3.52×10^{-2}	3.52×10^{-2}
Layer 7	5.48×10^{-2}	5.48×10^{-2}
Layer 8	7.24×10^{-4}	7.24×10^{-4}
Layer 9	8.00×10^{-4}	1.82×10^{-2}
Layer 10	7.69×10^{-4}	2.62×10^{-2}
Layer 11	7.46×10^{-4}	2.61×10^{-2}

5.6. 1648 bus system

5.6.1. Effects of different levels of data exchange

The effects of data exchange on contingency analysis are also performed for the 1648 bus system. As in the studies for the IEEE-118 bus system, not all topology changes in the external system of the 1648 bus system will be considered during contingency analysis. The following lines are considered for external outages – 243-246, 639-663, 656-687, 817-818, 1218-1220, 1305-1319 and 1438-1543. Each external line outage will constitute a case to be studied in contingency analysis.

The branches in the internal system with a large loading will be considered significant for contingency analysis, and 42 branches are selected for consideration in the studies for the 1648 bus system.

The approach for performing the contingency analysis studies are the same as that for the IEEE-118 bus system, which is already described in Section 5.5.1.

The contingency analysis accuracy metric for the 1648 bus system is as shown below:

$$J_{cont,1648} = \frac{1}{N}\sum_{i=1}^{N}\left[\sqrt{\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)\left(\vec{V_i} - \overrightarrow{V_i^{PF}}\right)^*}\right] \tag{5-5}$$

where $\vec{V_i}$ is the complex voltage at bus i from contingency analysis

$\overrightarrow{V_i^{PF}}$ is the complex voltage at bus i based on the exact power flow solution

N is the number of internal system buses

In Chapter 4, it was observed that there were some scenarios where data exchange with only a portion of the external system led to state estimation results which were erroneous and would fail to converge. Such scenarios would not be considered for contingency analysis and in this section only scenarios where the state estimation converges to a reasonable result will be considered for contingency analysis. These scenarios are shown in TABLE XLIV.

TABLE XLIV. Scenarios for investigation of effects of data exchange during state estimation on ensuing contingency analysis (Testbed system: 1648 bus system)

Scenario	Description
5D	Contingency analysis for the case where the state estimation solution is from a situation where data exchange is performed with Areas 2 and 3 of the external system. Pseudo measurements were made for Area 4 to ensure the external system remains observable.
5E	Contingency analysis for the case where the state estimation solution is from a situation where data exchange is performed with Areas 3 and 4 of the external system. Pseudo measurements were made for Area 2 to ensure the external system remains observable.
5F	Contingency analysis for the case where the state estimation solution is from a situation where data exchange is performed with Areas 2, 3 and 4 of the external system.

The mean values of the contingency analysis accuracy metric for all contingencies considered for each external line outage are illustrated in TABLE XLV.

TABLE XLV. Contingency analysis accuracy metric (Testbed system: 1648 bus system)

	Scenario		
	5D	5E	5F
Case (external outage on line)	$J_{cont,1648}$(Mean) for all n-1 contingencies considered		
243-246	0.001469	0.001601	0.001018
639-663	N/A	0.001844	0.000627
656-687	0.001097	N/A	0.001082
817-818	0.00093	N/A	0.000743
1218-1220	0.001029	0.001827	0.000904
1305-1319	0.001963	0.00085	0.001166
1438-1543	0.000601	0.00224	0.000466

From the TABLE XLV above, it can be seen that having knowledge of the entire external system provides the most accurate contingency analysis results in general. The scenarios with contingency analysis accuracy metric values marked N/A indicate that the state estimation results obtained for the corresponding level of data exchange had large errors in the external system which rendered it impossible to perform contingency analysis as they failed to converge. Recall that in Chapter 4, these scenarios did not display very large errors in the state estimation accuracy metric for the internal system. For Scenarios 5D and 5E, where SCADA data exchange is performed with 2 of the internal system's neighbors during state estimation, the contingency analysis accuracy metric attain larger values than for the case where perfect data exchange is possible. However, these values are not very large and do not indicate large errors during contingency analysis. Therefore, the mean values of the contingency analysis accuracy metric for all contingencies considered for each external line outage are illustrated in TABLE XLVI.

TABLE XLVI. Mean boundary bus errors for Scenarios 5D, 5E and 5F (Testbed system: 1648 bus system, Specific contingency cases)

	Scenario		
	5D	5E	5F
Case (external outage on line)	Mean of boundary bus errors		
243-246	0.026525	0.031421	0.017131
639-663	N/A	0.03417	0.011122
656-687	0.019681	N/A	0.019234
817-818	0.015482	N/A	0.0133
1218-1220	0.018973	0.032312	0.017589
1305-1319	0.035767	0.014955	0.023627
1438-1543	0.010225	0.040888	0.008405

It can be observed from TABLE XLVI that the boundary bus errors tend to be larger in Scenarios 5D and 5E for contingency analysis in general. This shows that while exchanging data over a relatively large portion of the external system provides decent state estimation results, there are still some detrimental effects on ensuing contingency analysis of the system.

5.6.2. Effects of topology errors

In the previous section, the effects of implementing various levels of data exchange with the external system during state estimation on ensuing contingency analysis were studied. The effects of having incorrect topology knowledge because of errors in the external system's topology process on contingency analysis are studied in this section. The approach is the same as that in the previous section, and additional scenarios are created in addition to Scenarios 5D, 5E and 5F, and they are described in TABLE XLVII.

TABLE XLVII. Scenarios for investigation of effects of topology errors in the data exchange process during state estimation on ensuing contingency analysis (Testbed system: 1648 bus system)

Scenario	Description
5G	Contingency analysis for the case where the state estimation solution is from a situation where data exchange is performed with Areas 2 and 3 of the external system. Pseudo measurements were made for Area 4 to ensure the external system remains observable. However, there is an error in the external system's topology processor and the internal system is unaware of any external line outages.
5H	Contingency analysis for the case where the state estimation solution is from a situation where data exchange is performed with Areas 3 and 4 of the external system. Pseudo measurements were made for Area 2 to ensure the external system remains observable. However, there is an error in the external system's topology processor and the internal system is unaware of any external line outages.
5I	Contingency analysis for the case where the state estimation solution is from a situation where data exchange is performed with Areas 2, 3 and 4 of the external system. However, there is an error in the external system's topology processor and the internal system is unaware of any external line outages.

TABLE XLVIII illustrates the results for data exchange with the entire external system. In the table, both the mean of the contingency analysis accuracy metric and the mean of the average boundary bus error for all n-1 contingencies considered are illustrated. It can be seen that both J_{1648} and the average boundary bus errors for all n-1 contingencies considered are higher in Scenario 5I as compared to Scenario 5F in general. Note that even though Scenario 5F represents the case where there is complete data exchange with the external system during state estimation, some level of error still exists at the boundary buses in the ensuing contingency analysis. Scenario 5I represents the situation where there is real-time data exchange with the external system during state estimation, but with the error of the topology processor in the external system, the internal state estimator fails to see the actual topology change, and hence, the topology data used during internal state estimation is wrong. It can be seen that this leads to even larger errors during contingency analysis. The importance of correct topology data during state estimation is once again observed in these studies.

TABLE XLVIII. Contingency analysis results for Scenarios 5F and 5I (Testbed system: 1648 bus system)

	Scenario			Scenario	
	5F	5I		5F	5I
Case (external outage on line)	$J_{cont,1648}$(Mean) for all n-1 contingencies considered			Mean of Mean of boundary bus errors for all n-1 contingencies considered	
243-246	0.001018	0.001402		0.017131	0.021524
639-663	0.000627	0.000925		0.011122	0.014579
656-687	0.001082	0.001592		0.019234	0.023899
817-818	0.000743	0.001868		0.0133	0.022876
1218-1220	0.000904	0.00067		0.017589	0.014039
1305-1319	0.001166	0.001826		0.023627	0.034092
1438-1543	0.000466	0.001129		0.008405	0.017533

The results for other scenarios where data exchange is only with certain areas of the external system are also illustrated below. TABLE XLIX shows the results for Scenarios 5D and 5G where data exchange is performed with Areas 2 and 3, and the difference in these scenarios are the existence of topology errors in Scenario 5G. For the case where the line 243-246 is out, the contingency analysis results are erroneous regardless of the existence of topology errors during state estimation. This is because line 243-246 is in Area 4, and the topology change is not known in either Scenario 5D or 5G during state estimation. Hence the state estimation results both contain errors, which lead to errors in ensuing contingency analysis. For the other external line outages, it appears that contingency analysis results are more accurate when correct topology data is used during state estimation. An exception is for the line outage on 1305-1319 where the boundary bus errors are fairly large. It appears that when contingency analysis results are erroneous enough in scenarios where there are no topology errors, the existence of topology errors may not necessarily cause further deterioration in contingency analysis accuracy.

TABLE XLIX. Contingency analysis results for Scenarios 5D and 5G (Testbed system: 1648 bus system)

	Scenario			Scenario	
	5D	5G		5D	5G
Case (external outage on line)	$J_{cont,1648}$(Mean) for all n-1 contingencies considered			Mean of Mean of boundary bus errors for all n-1 contingencies considered	
243-246	0.001469	0.001022		0.026525	0.017236
656-687	0.001097	0.00161		0.019681	0.024234
817-818	0.00093	0.002037		0.015482	0.024555
1218-1220	0.001029	0.000769		0.018973	0.015447
1305-1319	0.001963	0.001256		0.035767	0.024886
1438-1543	0.000601	0.001279		0.010225	0.019316

TABLE L shows the results for Scenarios 5E and 5H where data exchange is performed with Areas 3 and 4, and the difference in these scenarios are the existence of topology errors in Scenario 5H. As observed in the previous part, it appears that contingency analysis results are more accurate when correct topology data is used during state estimation. An exception is for line outages on 243-246 and 1438-1543 where the boundary bus errors are fairly large. It appears that when contingency analysis results are erroneous enough in scenarios where there are no topology errors, the existence of topology errors may not necessarily cause further deterioration in contingency analysis accuracy.

TABLE L. Contingency analysis results for Scenarios 5E and 5H (Testbed system: 1648 bus system)

	Scenario			Scenario	
	5E	5H		5E	5H
Case (external outage on line)	$J_{cont,1648}$(Mean) for all n-1 contingencies considered			Mean of Mean of boundary bus errors for all n-1 contingencies considered	
243-246	0.001601	0.001351		0.031421	0.028381
639-663	0.001844	0.001832		0.03417	0.035609
1218-1220	0.001827	0.002159		0.032312	0.036213
1305-1319	0.00085	0.001792		0.014955	0.026541
1438-1543	0.00224	0.001616		0.040888	0.031956

5.7. Summary

In this chapter, studies are first performed to determine the amount of the external model required to ensure a high level of internal state estimation accuracy. The studies are performed on the IEEE-118 bus system and it is investigate the effects of using different amounts of the external model during state estimation. It is noted the amount of the external model which is solved for has little effect on state estimation accuracy as long as knowledge of the system topology is correct. In the event that topology errors exist, it is possible that they are not seen during internal state estimation if the external model to be solved for does not cover the location of the topology change. This observation leads to the proposal of an algorithm to determine the proximity of topology errors in the external system. This algorithm is tested on the IEEE-118 bus system with two different solution methods and one of them is found to be successful in determining the proximity of topology errors from the internal system.

The effects of various levels of data exchange during state estimation on ensuing contingency analysis accuracy are then investigated on the IEEE-118 bus system. One of the key observations is that incorrect topology knowledge during state estimation can lead to large errors at the boundary buses in the ensuing contingency analysis results.

In the investigation of the effects of using different amounts of the external model, it is noted that contingency analysis results can have certain amounts of errors when the external model which is solved for is relatively small. These errors exist even when correct real-time data is exchanged during state estimation. It is also observed that highly accurate contingency analysis results are only guaranteed when almost the full system model is used during state estimation and ensuing contingency analysis.

Finally, the investigation of the effects of data exchange during state estimation on ensuing contingency was extended to the 1648 bus system. Similar results are obtained in that having correct topology knowledge during state estimation is crucial to ensuring accurate contingency analysis results.

6. CONCLUSIONS AND FUTURE WORK

6.1. Conclusions

In this dissertation, a set of studies have been conducted to investigate the effects of data exchange with the external system on state estimation accuracy and ensuing contingency analysis of multi-area power systems.

The IEEE-118 bus system was used as a testbed for all these proposed studies, and some of these studies were extended to a larger 1648 bus system to observe if similar trends could be discovered. The advantage of using these testbed systems was that the exact solution can be found through a power flow solution since all the system parameters are known already. Random errors were added to the state variables and dependent variables to create measurements for different cases representing different operating conditions. A state estimation metric was then proposed to illustrate the accuracy of state estimation under different scenarios representing different levels and types of data exchange since the exact solutions are known.

Tests were first performed to determine the importance of having correct real-time data of the external system in state estimation when the detailed external model is used. It was noted that the lack of data exchange would lead to large errors in state estimation when there are sufficiently large changes in the system operating conditions from the base case operating conditions.

Then, studies were conducted to investigate the effects of different levels of data exchange on internal state estimation accuracy. The IEEE-118 bus system was configured as a multi-area system to represent the real situation where each control area is connected to other control centers. Scenarios were then created to represent data exchange with select areas of the external system during state estimation. The main finding was that performing data exchange with only select areas of the external system would not always guarantee improved state estimation accuracy. This observation was even more pronounced in cases where obtaining real-time data over a larger area of the system still does not provide the internal system's control center with correct topology knowledge during state estimation.

These studies were extended to the 1648 bus system and similar trends were observed for the 1648 system. Some new findings were that the state estimator would not always converge when data exchange is only performed with small portions of the external system and the rest of the external system is represented by pseudo measurements from the base case operating conditions. This illustrated one of the main difficulties of performing state estimation with detailed external models in large power systems, since sufficient real-time data across the system must be available to ensure a certain level of state estimation accuracy.

A set of studies was then conducted on the IEEE-118 bus system to compare the effects of exchanging SCADA data versus state estimated data with the external model for internal state estimation. It was observed that exchanging either SCADA data or state estimated data would give highly accurate state estimation results in the event that the real-time data exchanged is correct. An interesting observation was that exchanging state estimated data appeared to alleviate the issue of errors in the external system's topology processor and the results would be less erroneous than those for SCADA data exchange.

The effects of topology errors during SCADA data exchange were studied on the 1648 bus system, and it was noted that incorrect knowledge of the system topology during state estimation could lead to large errors in state estimation results even if the real-time analog data obtained from neighboring utilities is correct.

Another interesting issue in power system state estimation relates to how much of the external model is required to ensure accurate state estimation results and ensuing contingency analysis. Studies were performed on the IEEE-118 test bed system once again. It was noted that while the amount of the external model solved for during state estimation has little effect on internal state estimation accuracy, a sufficient large portion of the external model has to be solved for in order to guarantee accurate contingency analysis results. An algorithm was proposed to determine the proximity of external topology errors based on the idea of comparing successive state estimation metric values as the amount of the system model to be solved for grew in size. This algorithm was tested on the IEEE-118 bus system and found to be successful in determining the proximity of topology errors in the external system.

The importance of accurate state estimation is important to the accuracy of ensuing EMS functions such as contingency analysis. Therefore, the effects of various types and levels of data exchange during state estimation on ensuing contingency analysis accuracy were investigated on the IEEE-118 bus system and the 1648 bus system.

One of the key observations for both systems was the correct topology knowledge during state estimation is crucial to ensuring accurate contingency analysis results. It was noted that the existence of topology errors during data exchange would cause contingency analysis results to deteriorate even if data exchange was performed with the entire external system to obtain real-time analog measurements.

Another observation was that retaining a larger portion of the external model would be necessary for ensuring accurate contingency analysis results. It was illustrated on the IEEE-118 bus system that solving the state estimator up to different layers of the external system would provide accurate state estimation results as long as the real-time data (both analog measurements and topology data) are both correct. However, moderate errors would still be noted in the contingency analysis results when insufficient amounts of the external system were retained.

In summary, these studies can be performed on other power systems during planning studies to determine the requirements for data exchange with external systems to ensure a high level of state estimation accuracy. Studies similar to those performed in this dissertation can also be performed to help determine how much of the external model is to be retained to have a certain level of accuracy in ensuing contingency analysis as well.

REFERENCES

[1]. A. Abur, A. G. Exposito, “Power System State Estimation – Theory and Implementation”, New York, Marcel Dekker, 2004.

[2]. F. C. Schweppe, J. Wildes, “Power System Static-State Estimation, Part I: Exact Model”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, no. 1, pp. 120-125, January 1970.

[3]. F. C. Schweppe, D. R. Rom, “Power System Static-State Estimation, Part II: Approximate Model”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, no. 1, pp. 125-130, January 1970.

[4]. F. C. Schweppe, “Power System Static-State Estimation, Part III: Implementation”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-89, no. 1, pp. 130-135, January 1970.

[5]. A. Monticelli, “State Estimation in Electric Power Systems: A Generalized Approach”, Boston, Kluwer Academic 1999.

[6]. A. Bose, “Modeling of External Networks for On-Line Security Analysis”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-103, no. 8, August 1984.

[7]. United States Department of Energy and Federal Energy Regulatory Commission, “Steps to Establish a Transmission Monitoring System for Transmission Owners and Operators within the Eastern and Western Interconnections”, February 2006.

[8]. T. Van Cutsem, M. Ribbens-Pavella, “A Two-Level Static State Estimator for Electric Power Systems”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, no. 8, pp. 3722-3732, August 1981.

[9]. M. S. Kurzyn, “Real-Time State Estimation for Large-Scale Power Systems”, IEEE Transactions on Power Apparatus and Systems, PAS-102, no. 7, pp. 2055-2063, July 1983.

[10]. L. Zhao, A. Abur, “Multi area state estimation using synchronized phasor measurements”, IEEE Transactions on Power Systems, vol. 20, no. 2, pp. 611-617, February 2005.

[11]. A. J. Conejo, S. De la Torre, M. Canas, “An Optimization Approach to Multiarea State Estimation”, IEEE Transactions on Power Systems, Vol. 22, no. 1, pp. 213-221, January 2007.

[12]. M. Y. Patel, A. A. Girgis, “Two-Level State Estimation for Multi-Area Power System”, Proceedings of the IEEE Power Engineering Society General Meeting, 2007.

[13]. W. Jiang, V. Vittal, G. T. Heydt, “A Distributed State Estimation Utilizing Synchronized Phasor Measurements”, IEEE Transactions on Power Systems, Vol. 22, no. 2, pp. 563-571, February 2007.

[14]. Th. V. Cutsem, J. Howard, M. Ribbens-Pavella, “Hierarchical State Estimation”, International Journal of Electrical Power and Energy Systems, Vol. 2, pp. 70-80, 1980.

[15]. K. A. Clements, O. J. Denison, R. J. Ringlee, “A multi-area approach to state estimation in power system networks”, Proceedings of the IEEE Power Engineering Summer Meeting, San Francisco, 1973.

[16]. K.L. Lo, M.M. Salem, R.D. McColl, A. M. Moffatt, “Two-level state estimation for large power system. I. Algorithms and II. Computational experience”, IEEE Proceedings Generation, Transmission, Distribution, Part C, vol. 135, no. 4, pp. 299-318.

[17]. D. M. Falcao, F. F. Wu, L. Murphy, “Parallel and Distributed state estimation”, IEEE Transactions on Power Systems, Vol. 10, no. 2, pp. 724-730, February 1995.

[18]. T. Van Cutsem, M. Ribbens-Pavella, “Critical Survey of Hierarchical Methods for State Estimation of Electric Power Systems”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, no. 10, pp. 3415-3424, October 1983.

[19]. A. G. Exposito, Antonio de la Villa Jaen, C. Gomez-Quiles, P. Rousseux, Th. V. Cutsem, “A taxonomy of multi-area state estimation methods”, Electric Power Systems Research, Vol. 81, no. 4, pp. 1060-1069, April 2011.

[20]. K. Kato, “External Network Modeling - Recent Practical Experience”, IEEE Transactions on Power Systems, Vol. 9, No. 1, January 1994.

[21]. R. Emami, A. Abur, “Impact of synchronized phasor measurements on external network modeling”, Proceedings of the North American Power Symposium, Calgary, Canada, September 2008.

[22]. A. Bose, “The Effects of External Modeling Errors on On-Line Security Analysis”, IEEE Transactions on Power Systems, Vol. 1, no.1, January 1986.

[23]. S. Deckmann, A. Pizzolante, A. Monticelli, B. Stott, O. Alsac, “Studies on Power System Load Flow Equivalencing”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, no. 6, November 1980.

[24]. S. Deckmann, A. Pizzolante, A. Monticelli, B. Stott, O. Alsac, “Numerical Testing of Power System Load Flow Equivalents”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-99, No. 6, November 1980.

[25]. F. F. Wu and A. Monticelli, “Critical review on external network modeling for online security analysis”, International Journal on Electrical Power and Energy Systems”, Vol. 5, no. 4, pp. 222-235, October 1983.

[26]. J. B. Ward, “Equivalent Circuits for Power-Flow Studies”, Transaction of the AIEE, Vol. 68, no. 1, pp. 373-382, 1949.

[27]. J. F. Dopazo, M. H. Dwarakanath, J. J. Li, A.M. Sasson, “An external system equivalent model using real-time measurements for system security evaluation”, IEEE Transactions on Power Apparatus and Systems, Vol. 96, no. 2, pp. 431-446, March 1977.

[28]. R.A.M. van Amerongen, K.P. van Meeteren, “A Generalized Ward Equivalent for Security Analysis”, IEEE Power Engineering Review, Vol. PER-2, no. 6, pp. 42-43, June 1982.

[29]. W.L. Snyder, “Load Flow Equivalent Circuits - An Overview”, Proceedings of the IEEE PES Winter Meeting, New York, January 1972.

[30]. H. Duran, N. V. Arvanitidis, “Simplifications for Area Security Analysis: A New Look at Equivalence”, IEEE Transactions on Power Apparatus and Systems, vol. PAS-91, pp. 670-679, March 1972.
[31]. E.L. Paulson, “Network Equivalents for On-Line Systems”, Proceedings of the IEEE PES Summer Meeting, Anaheim, July 1974.
[32]. D. Denzel, R. Graf, J. Verstege, “Practical Use of Equivalents for Unobservable Networks in On-Line Security Monitoring”, Proceedings of the PSCC, Cambridge, September 1975.
[33]. A. Monticelli, S. Deckmann, A. Garcia, B. Stott, “Real-Time External Equivalents for Static Security Analysis”, IEEE Transactions on Power Apparatus and Systems, vol. PAS-98, pp. 498-508, March 1979.
[34]. F.C. Aschmoneit, J.F. Verstege, “An External System Equivalent for on-line Steady-State Generator Outage Simulation”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, no. 3 pp. 770-779, May 1979.
[35]. P. Dimo, “Nodal Analysis of Power Systems”, Abacus Press, Kent, England, 1975.
[36]. W. F. Tinney, W. L. Powell, “The REI Approach to Power Network Equivalents”, Proceedings of the PICA Conference, Toronto, May 1977.
[37]. T. E. Dy Liacco, S. C. Savulescu, K. A. Ramarao, “An On-Line Topological Equivalent of a Power System”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-97, no. 5, pp.1550-1563, September 1978.
[38]. G. Irisarri, A. M. Sasson, J. F. Dapazo, “Real-Time External System Equivalent for On-Line Contingency Analysis”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, no. 6, pp. 2153-2171, November 1979.
[39]. F. F. Wu and N. Narasimhamurthi, “Necessary Conditions for REI Reduction to be Exact”, Proceedings of the IEEE PES Winter Meeting, New York, 1979.
[40]. S. C. Savulescu, “A Class of Topological Equivalents for Power Systems”, Proceedings of the PSCC, Darmstadt, August 1978.
[41]. S. C. Savulescu, “Equivalents for Security Analysis of Power Systems”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-100, no. 5, pp. 2672-2682, May 1981.
[42]. A. Bose, “On-Line Network Programs for Power System Control”, Proceedings of the Midwest Symposium on Circuits and Systems, Ames, IA, August 1978.
[43]. S. A. Arefeh, R. Schinzinger, “Estimation Algorithms for Large-Scale Power Systems”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-98, no. 6, pp. 1968-1977, November 1979.
[44]. J. C. Russell, W. Rades, “The Wisconsin Electric Power Company Energy Control System – An Update”, Proceedings of the Power Industry Computer Applications Conference, Minneapolis, Minnesota, 1973.
[45]. W. R. Cassel, A. J. Zetlan, R. E. Hansen, D. W. Bree, R. D. Masiello, “The Delmarva Power and Light Energy Control System”, Proceedings of the IEEE Power Engineering Society Power Industry Applications conference, 1977.
[46]. B. K. Mukherjee, S. O. Hanson, L. L. Hung, S. M. Hoyt, A. L. Gregson, “The Union Electric Company Load Dispatch System”, Proceedings of the IEEE Control of Power Systems Conference, Oklahoma City, March 1980.

[47]. J. S. Horton, D. Gustafson, K. Vormwald, W. C. Bruns, W. R. Prince, E.E. Taylor, “The Baltimore Gas and Electric Company Energy Control System – An Overview”, Proceedings of the Power Industry Computer Applications Conference, Philadelphia, PA, May 1981.

[48]. K. Geisler, A. Bose, “State Estimation Based External Network Solution for on-line Security Analysis”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-102, no. 8, Aug 1983.

[49]. A Monticelli, Felix F. Wu, “A Method That Combines Internal State Estimation and External Network Modeling”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, no. 1, Jan 1985.

[50]. M. Y. Patel, A. A. Girgis, “A Comparison of State Estimation Based External Network Modeling Methods”, Proceedings of the Power Systems Conference: Advanced Metering, Protection, Control, Communication, and Distributed Resources, March 2006.

[51]. K. I. Geisler and N. K. Tripathi, “State Estimation Based External Network Solutions: Field Testing”, IEEE Transactions on Power Apparatus and Systems, Vol. PAS-104, no. 8, pp. 2126-2132, August 1985.

[52]. C. N. Lu, K. C. Liu, and S. Vemuri, “An external network modeling approach for online security analysis”, IEEE Transactions on Power Systems, Vol. 5, no. 2, pp. 565-573, May 1990.

[53]. P. Sanderson, R. Curtis, D. Athow, C. N. Lu, K. C. Liu, C. Letter, “Real time complete model estimation for contingency study: field experience”, IEEE Transactions on Power System, Vol. 6, no. 4, pp. 1480-1484, Nov 1991.

[54]. Metrics for Determining the Impact of Phasor Measurements on Power System State Estimation, Eastern Interconnection Phasor Project, March 2006.