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Network reduction of power system for transient stability studies

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Abstract: Modern power systems are complicated and heavily interconnected systems. Hence critical analysis of the network for power system planning is very important. Challenges in analyzing large interconnected networks have given rise to the need to find small, equivalent networks in order to improve computational efficiency. There are many methods for determining an equivalent network which accurately represents the original network. In this paper Thevenin's method is used to calculate the equivalent of a system. The PSS/E software is used to demonstrate the method for separation of a particular area network from all-India network by placing dynamic equivalents at the boundary buses.

Keywords: *boundary buses, dynamic equivalent, internal and external systems, transient stability.*

1.0 INTRODUCTION

Uncertainties in load growth, increase in penetration of renewable energies, increased use of power electronic converters and growing competitiveness of electricity markets have led to the operation of the power system under heavily loaded and critical conditions. The overall characteristics of the power systems are constantly under change. Hence it is imperative for the power systems planners, to not only analyze the power system accurately but also in a quick and efficient manner. Hence, modelling of the power system plays an important role in its efficient analysis.

Large interconnected power systems are difficult to handle. By using small, equivalent systems which are representative of the original network the computational requirements can be reduced. Some of the reasons for using a reduced model are [1]: (i) A typical interconnected power system consists of number of areas owned by various utilities which are reluctant to share complete information among one another. (ii) Practical limitations on computational resources. (iii) As the electrical distance from the point of interest increases, the requirement of detailed modelling of remote location decreases (iv) With the help of optimally placed measuring instruments, such as Phasor Measurement Units (PMU), it may be more efficient to calculate equivalents at boundary buses.

It must be noted that achieving faster simulation and optimization times is not the only goal for applying the model reduction [2]. Sometimes, it is most important to get the model with the lowest number of variables. For example, world-wide power systems increase in size and complexity year-by-year due to the rapid growth of widespread interconnections and much higher penetration of distributed resources. Today, the interconnected power systems cover large geographical areas and comprise thousands of devices, so the dimension of the models may easily reach the order of several thousands of state variables and more. For such large-scale

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power systems and their full detailed models, it is neither practical nor necessary to perform dynamic studies such as stability studies and dynamic security assessment.

Network reductions techniques are generally classified as static and dynamic based on the model representation and its intended use [3]. Static reductions model the equivalent as a snapshot of the system and is used for static analysis such as power flow calculations, system planning and operational studies. Dynamic reduction techniques are intended for analysis of dynamic effects such as large scale power system transient analysis for large and small disturbances and power system security assessment. The term network reduction in this paper refers to 50Hz equivalent of the system that can be used for static and dynamic studies.

The idea of partitioning the interconnected system into internal and external systems was first given by Ward, who originally proposed the technique of network reduction in [4]. In Ward's method, the external system is removed by Gaussian elimination. This method was developed along the years and modified as extended Ward equivalent method by A. Monticelli et.al [5]. The Ward method and its variations are the most popularly used methods for finding equivalents.

Another type of method is the REI (Radial Equivalent independent) network reduction technique, first discussed in [6]. Further development of the method was done in [7] and [8]. The main idea is to identify a group of similar nodes and to replace each group by one virtual node. The power injection at this virtual node is equal to the aggregated injections of the group of nodes that will be replaced, and the aggregated nodes become passive.

The generalities of equivalencing is explained in detail in [9]. The interconnected system can be divided into two parts: an "internal" subsystem and an "external" subsystem as shown in Fig.1. In practice, the area under consideration is usually modelled as the internal system. The rest of the network is modelled as the external system and is connected to the internal system via tie lines. Boundary buses are those buses connecting the external system and the tie lines, as shown in Fig. 1. In power system analysis tools, the internal system is modelled in detail and the external system is usually represented by equivalent models. According to the authors in [9], there are three modes in which an equivalent can be calculated based on the availability of data.

i). *Mode 1*: The solved load-flow model of the entire interconnected system is available. This mode is applicable in power system planning. This mode is used only for simple reduction of system size.

ii). *Mode 2*: The solved load flow model of the internal system is available. Data for corresponding external system not precise. This mode is used for producing the best possible external model using whatever information available. Mostly used in on-line applications like state estimation.

iii). *Mode 3*: An unsolved model of the internal system is available. A separately obtained external equivalent is to be attached to it, before load-flow solution can be run. This mode is used in power system expansion planning.

This paper deals with construction of equivalent in accordance to Mode 1, where the solved load flow model of the entire interconnected system is available. The main aim of such equivalencing is to achieve reduced network for transient stability studies.

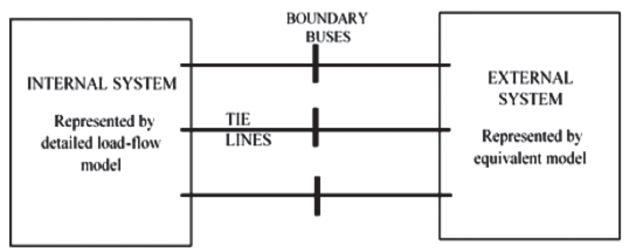

FIG. 1 EQUIVALENCING IN INTERCONNECTED SYSTEMS.

The authors in [9] have proposed the following basic properties for an equivalent system

1) The equivalent system should be a reliable accurate model of the external system's effect on the internal system.
2) The equivalent model must not cause any load flow solution convergence or precision problems.
3) The equivalent model must be as computationally economical as possible.
4) The equivalent model should be such that the study system can be solved by standard load flow and other programs. This maybe mandatory feature in some equivalencing methods where inter-state data exchange is not available.
5) Certain external buses may be retained in the equivalent system for simulating generation outage, network enhancement, to adjust power flow interchanges and other such studies.

The equivalents attached to the internal system must not alter the present internal system states. In other words, the power flows from the equivalents into the boundary buses must exactly match the tie line flows. Boundary matching is inherent in some equivalencing methods, where the equivalent can be derived from an external system state (Mode 1). Otherwise, the equivalent model being used must undergo some adjustments, to contribute to the required power flows at the boundary buses (Mode 2).

In [1], the authors have compared the various methods for determining the equivalents and have concluded that the REI method is best suited for static reduction of power systems.

According to Thevenin's theorem [10], any black box that contains impedances, linear voltage and current sources, can be replaced by an equivalent circuit consisting of an equivalent voltage source connected in series with an equivalent impedance as shown in Figure 2.

In the Thevenin's equivalent circuit, if the terminals *A* and *B* are shorted, the current flowing from *A* to *B* is V_{TH}/Z_{TH}. This means that Z_{TH} could alternatively be calculated as V_{TH} divided by the short circuit current between *A* and *B* when they are connected together. Thevenin's equivalent is similar to REI reduction, where group nodes are replaced by a voltage source in series with an impedance.

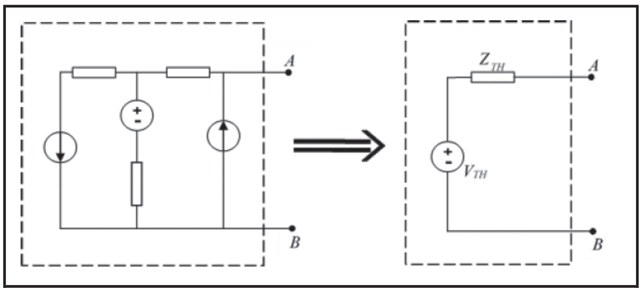

FIG. 2 THEVENIN'S EQUIVALENT CIRCUIT

Various software packages like E-TRAN, PSS/E, Dig SILENT Power Factory and Power World simulator can be used for obtaining equivalent network. In this paper, Short circuit (Thevenin's) equivalents are calculated at the boundary buses with the help of PSS/E (Power System Simulation for Engineering) software. The proposed method is tested on the All-India network (external system) for which the solved load flow data and sub-transient reactance data of the synchronous machines was available. The Kerala network (internal system) is separated from the rest of the network and the methodology adopted is given in subsequent section.

2.0 DETERMINATION OF EQUIVALENTS

When the external system is replaced by a Thevenin's equivalent, the equivalent must supply the same fault current as the external system would have supplied at the boundary bus. This is illustrated in Fig. 3

Once the short circuit current at the point of equivalencing in known, then the Thevenin's equivalent impedance can be calculated from Thevenin's theorem. The short circuit MVA of the equivalent source can be calculated from (1)

$$MVA_{SC} = \sqrt{3} \times V_{L-L} \times FC \qquad (1)$$

Where, FC is Fault Current in kilo amperes, V_{L-L} is the line-to-line RMS voltage in kilo Volts at the boundary bus and MVA_{SC} is the short circuit MVA and

$$Z_{TH} = \frac{V_{L-L}{}^2}{MVA_{SC}} \quad (2)$$

Z_{TH} is the Thevenin's impedance of the equivalent in ohms.

The power injections (or power absorption, depending on power exchange at the boundary bus) are the same for the equivalent source as that of the external system.

The PSS/E software can be used to quickly and efficiently calculate the short circuit currents at a particular bus. The software calculates short circuit currents in accordance to IEC-60909 standard taking into account the sub-transient reactances of the synchronous machines. Hence, it is very accurate method to determine the equivalent of the external system at the boundary buses using PSS/E

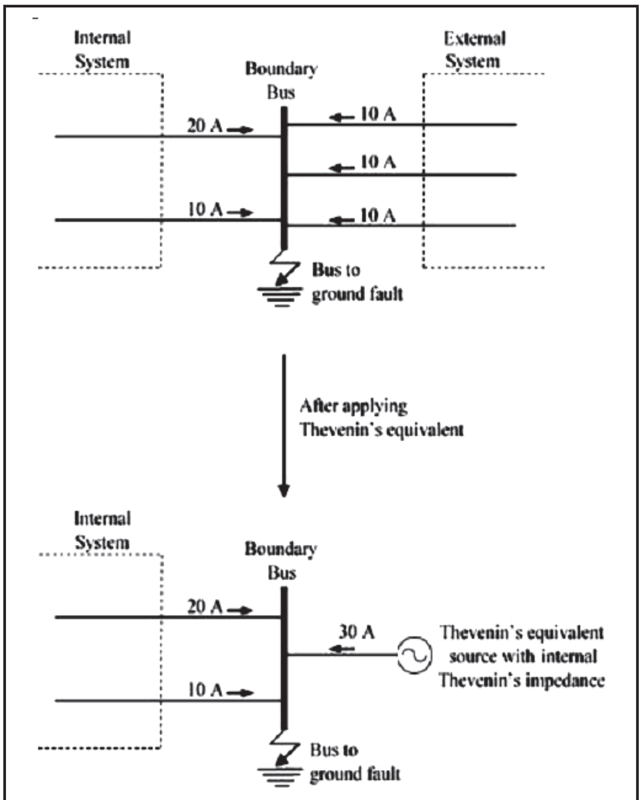

FIG. 3 THEVENIN'S EQUIVALENT AT BOUNDARY BUSES SUPPLYING THE SAME SHORT CIRCUIT CURRENT AS THE EXTERNAL SYSTEM

3.0 SIMULATION RESULTS FROM PSS/E

All-India network system, which consists of 6731 buses (50No. of 765 kV buses, 540No. of 400 kV buses, 1556 No. of 220 kV buses, 130 No. of 230 kV buses, 3078 No. of 132 kV buses, 1015No. of 110 kV buses, 33No. of 100 kV buses, 282 No. of 66 kV buses, 44No. of 33 kV buses and 3No. of 11 kV buses). 2027 No. of synchronous machines, 13246 No. of AC lines and 17No. of 2 terminal DC lines. This network is used to extract the Kerala state system, consisting of 38 buses (with 12 tie lines, 3No. of 230 kV buses, 30No. of 220 kV buses and 5No. of 400 kV buses) which is considered as the internal system for Network reduction concepts in PSS/E. The reduced network consists of seven boundary buses where the Thevenin's equivalent has been calculated. In order to find the equivalent at the boundary buses, three phase-to-ground fault is applied and the short circuit currents flowing into the boundary buses are determined. The short circuit currents supplied by the external system and the equivalent source are compared at each boundary bus and tabulated in Table I.

TABLE 1

COMPARISON OF SHORT CIRCUIT CURRENTS BETWEEN EXTERNAL SYSTEM & EQUIVALENT SOURCE

Boundary Bus number	**Short circuit current** supplied by external system (A)	**Short circuit current** supplied by equivalent source (A)
Bus 1	17887.39	17887.39
Bus 2	20927.13	20927.13
Bus 3	6045.44	6045.44
Bus 4	8089.73	8089.73
Bus 5	5301.40	5301.40
Bus 6	6312.00	6312.00
Bus 7	12470.51	12470.51

The comparison of bus voltages at the boundary buses between the original and the reduced network is tabulated in Table II.

TABLE 2		
COMPARISON OF BUS VOLTAGE BETWEEN ORIGINAL AND REDUCED NETWORK		
Boundary Bus number	Complex bus voltage in original network (p.u.)	Complex bus voltage in reduced network (p.u.)
Bus 1	1.00068 ∠-68.35^0	1.00069 ∠-68.35^0
Bus 2	0.96036 ∠-75.56^0	0.96032 ∠-75.56^0
Bus 3	0.96986 ∠-74.07^0	0.96986 ∠-74.08^0
Bus 4	0.96784 ∠-81.02^0	0.96783 ∠-81.02^0
Bus 5	1.00880 ∠-71.40^0	1.00880 ∠-71.41^0
Bus 6	0.96941 ∠-81.53^0	0.96941 ∠-81.54^0
Bus 7	0.97420 ∠-77.85^0	0.97421 ∠-77.85^0

The comparison of the complex power flow through the boundary buses between the original and reduced network is tabulated in Table III.

TABLE 3		
COMPARISON OF COMPLEX POWER AT BOUNDARY BUSES BETWEEN ORIGINAL & REDUCED SYSTEM		
Boundary Bus Number	Complex Power Injection In Original Network (Mva)	Complex Power Injection In Reduced Network (Mva)
Bus 1	471.4 + j 22.2	471.4 + j 22.2
Bus 2	84.9 – j 73.3	84.9 – j 73.3
Bus 3	22.0 – j 46.2	22.0 – j 46.0
Bus 4	423.2 + j134.0	423.3 + j 134
Bus 5	446.8 + j 113.6	446.8 + j113.5
Bus 6	135.2 + j 21.0	135.2 + j 21.0
Bus 7	375.6 + j 69.6	375.6 + j 69.6

As seen from Table II and Table III, the Thevenin's equivalent method gives accurate results with respect to both bus voltage and power flowing at the boundary buses. It is assumed that no boundary bus is part of a HVDC terminal, i.e. there are no DC boundary buses. The Thevenin's method is a static method and used for computation at fundamental frequencies. While carrying out Electro Magnetic Transient studies like Switching transient studies and Insulation co- ordination studies the frequency dependent network equivalent has to be calculated in order to include the contribution of the other frequencies. In [11], the authors have proposed a method for calculating the frequency dependent AC equivalents using the concept of resonance matching in parallel RLC systems.

4.0 CONCLUSIONS

Network reductions are widely used in power system applications. Constraints in computation, data storage and communication capacity necessitates the concept of network reduction. All network reduction methods utilize some form of aggregation of an external network. The basic theory is to consider the effect of external network as representative as possible when reducing the network to carry out the studies in the desired frequency range. This paper aims to compute the dynamic equivalents in a simple and accurate way for transient stability studies by using the concept of Thevenin's equivalents. The PSS/E software is used to calculate short circuit currents at the boundary buses, which leads to quick determination of Thevenin's equivalent. At boundary buses bus voltages, power flows and short circuit currents are compared between the original networks and reduced network and found that they are exactly matching. Hence this method of equivalencing is accurate for dynamic analysis.

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