Voltage Stability Assessment of The National Grid System Using Modern Analytical Tools

Ricardo R. Austria, Xiaokang Xu and Michael Power

***Abstract*--The paper presents a three-step analytical approach to identifying voltage stability concerns using modern network analysis tools. The first step in the analytical approach is to develop a load flow model for contingency analysis. This allows the identification of system steady-state low voltages or voltage collapses following contingencies. The second step is to apply an optimization algorithm/model to determine the reactive margin, or the amount and location of reactive compensation required to eliminate the low voltages or voltage collapses. P-V or Q-V curves are generated for comparison in this step. The final step is to verify the voltage stability response to the contingencies via time-domain simulation, including the impact of different load models.**

***Index Terms*--contingency analysis, long term dynamic simulation, optimal power flow, voltage collapse, and voltage stability.**

I. INTRODUCTION

VOLTAGE stability is an important concern in many power systems. With the advent of open generation markets and the use of transmission systems beyond their planned basis, this has become even more important. Assessing for voltage stability, however, has remained an almost purely technical issue, outside of the attention of market forces. This paper seeks to provide an overview of the phenomena, and the methods of assessment and measurement using modern network analysis tools. To illustrate practical applications, we are drawing from a study conducted on the Irish Electricity Supply Board (ESB) National Grid.

The paper presents a three-step analytical approach to identifying voltage stability concerns. The first step in the analytical approach is to develop a load flow model for contingency analysis. This allows the identification of system steady-state low voltages or voltage collapses following contingencies. The second step is to apply an optimization algorithm/model to determine the reactive margin, or the amount and location of reactive compensation required to eliminate the low voltages or voltage collapses. P-V or Q-V curves are generated for comparison in this step. The final step is to verify the dynamic voltage stability response to the contingencies via time-domain simulation, including the impact of different load models.

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II. ANALYTICAL TOOLS AND MODELS

The analytical tools and models used in this study include:

- AC contingency Analysis
- Optimal Power Flow (OPF)
- Reactive-Voltage (Q-V) & Power-Voltage (P-V) curves
- Long term dynamic simulation

AC contingency analysis is based on an ac load flow model, referred to as the TPLAN[1] model in the following discussions. This model uses an advanced enumeration and ranking technique which can analyze up to several thousand specified or automatically selected single and multiple contingencies [1]. Fig. 1 shows contingency analysis process implemented in the TPLAN model.

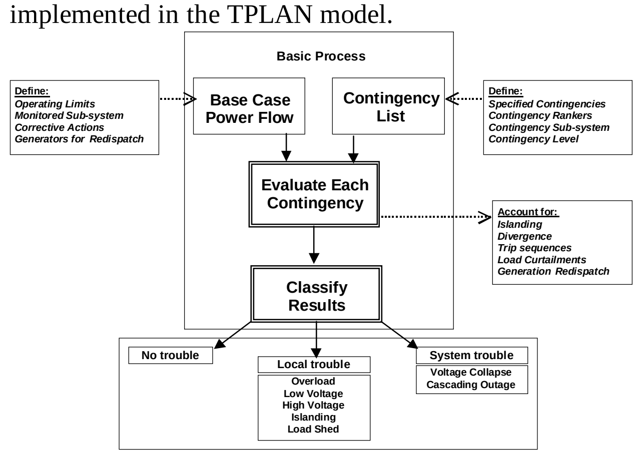

Fig. 1. Automatic Contingency Analysis Process

The TPLAN model is also incorporated with a Non-Divergent Power Flow Solution (NDPF), as shown in Fig. 2, for identifying a state of voltage collapse. The bottom block of Fig. 2 is where voltages are updated prior to the next iteration. In NDPF, this is modified to:

$$E_{new} = E_{old} + \mu \Delta E \tag{1}$$

Where μ is a scaling factor that is initially set to 1.0. If the mismatches that result from E_{new} indicate divergence, the value of μ is reduced, and the mismatches recalculated. This process is repeated until either the indication of divergence is eliminated or μ has been reduced to near zero value. When μ is near zero, the Jacobian is approaching singularity. This condition is defined as a voltage collapse from the steady-state viewpoint.

[1] *TPLAN is the commercial tradename for PTI's reliability assessment software.*

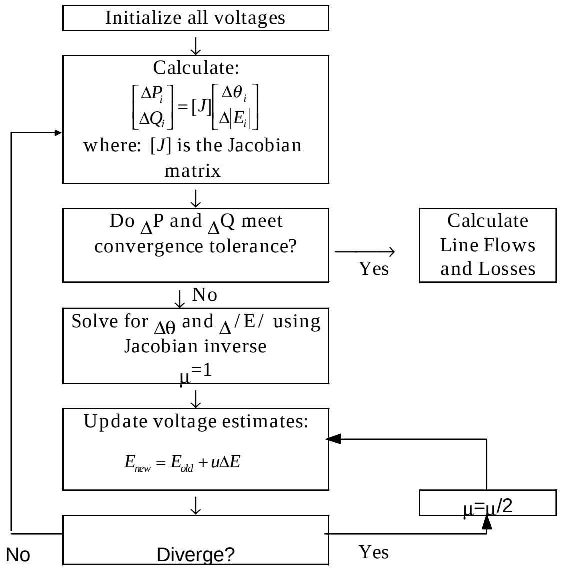

Fig. 2. Non-Divergent Power Flow Solution Algorithm

The TPLAN model is used to identify critical contingencies leading to low voltages or voltage collapse. The critical contingencies identified by TPLAN are further analyzed using an OPF model implemented in PSS/E[2]. This model applies an interior point algorithm based on the Newton and Kuhn-Tucker methods for solving a nonlinear problem consisting of an objective function and a combination of equality and inequality constraints [2][3]. The results of executing the OPF model are the locations and amount of reactive compensation required to eliminate low voltages or voltage collapse. Collectively, these could be referred to as the "reactive margin". In addition, the amount of compensation calculated by OPF indicates relative severity of the critical contingencies and therefore the worst contingencies can be identified.

For the purpose of comparison, system and capacitor Q-V curves under post-contingency conditions are also generated by running a series of load flows for a range of voltages at the buses of concern. The voltage levels are held by a synchronous condenser model ignoring Mvar limits at the selected bus in the load flows. The system Q-V relationship shows the sensitivity and variation of bus voltages with respect to reactive power injection or absorption, while the capacitor Q-V curves gives the relationships between voltage and the reactive power produced by shunt capacitors.

In a power system, reactive generation is consumed by reactive loads and high transmission use such as may come about from carrying large power transfers and transactions. At high demand and/or high transmission loading, system voltages drop. Knee-of-the-curve analysis using P-V curves capture the voltage aspects of this effectively. P-V curves are obtained by solving a series of power flows starting from a low transfer level and increasing in steps. The MW of incremental transfer that can be accommodated from the starting condition to the point voltage instability is the real power reserve to voltage instability. Figs. 3 & 4 show a sample application of such analysis tool.

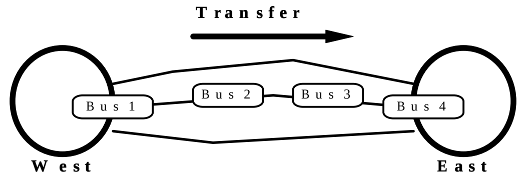

Fig. 3. Voltages Measured at Various Points along a Transfer Path

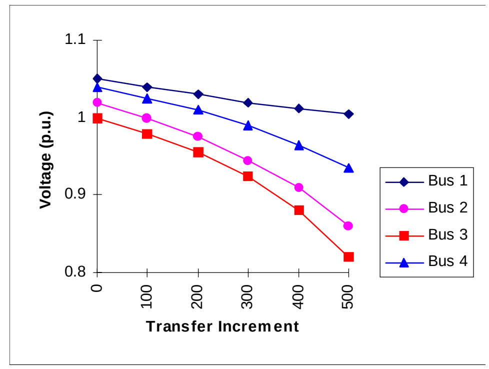

Fig. 4. P-V Curves Measured at Different Locations on the Transfer Path

After the TPLAN, OPF, P-V and Q-V curve analysis, system voltage stability is further analyzed by performing long term dynamic simulations. Long term simulations differ from transient stability studies with respect to certain long term phenomena. These effects include:

- The movement of on-line tap changers (OLTC)
- The effect of maximum excitation limiters (MEL)
- The self-restoration of loads to pre-contingency levels
- The effect of protective relaying

The OLTC model allows the modeling of slower transformer tap adjustments to help control system voltage during a long term dynamic simulation. Referring to Fig. 5, OLTC has two main components [4]. The first is the voltage sensor, which compares the input voltage to the pre-selected setting (voltage level) and a tolerance, or spread, in voltage level (bandwidth). If the voltage input to the sensor is out of the control band, the control will operate after the time delay has been exceeded. Thus, the output of the regulator will be either raised or lowered until the voltage feedback into the sensor is again within the control band. Since the time delay is generally magnitudes greater than the voltage sensor transducer time constant, the transducer time constant is not modeled.

The second major component of OLTC is the time-delay circuit. It permits the regulator to ignore brief, self-correcting voltage variations. The time delay enables the transformer to correct only those voltage variations which exist for longer than a preset time. The time delay for subsequent tap changes can be specified independently of the first time delay. OLTC incorporates the most common type of timer, an integrator,

[2] *PSS/E is the commercial tradename for PTI's transmission planning and operation software.*

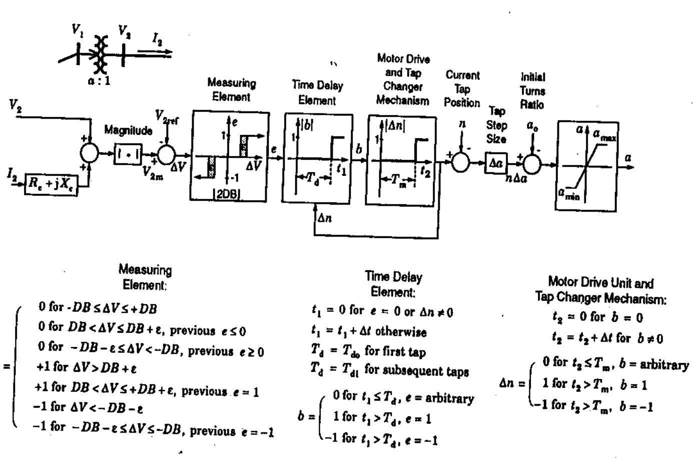

Fig. 5. OLTC Model

which adds the total amount of time that the voltage is outside the pre-selected control band and subtracts the time it is inside the control band. When the voltage is outside more than inside by an amount greater than the time-delay setting, T_d , the time-delay sends a tap signal to the tap changer motor. The tap changer motor operates T_m seconds later. Typical data for this model would be 25 seconds for T_d and 10 seconds for T_m.

The MEL model protects the generator field of an ac machine with automatic excitation control from overheating. This may come about due to prolonged overexcitation from failure of a component of the voltage regulator or an abnormal system condition which demands higher reactive power output from the machine. It allows limiting of either field voltage or field current. The model assumes an inverse time characteristic, i.e., operating time is a function of the magnitude of the overvoltage, as shown in Fig. 6. The block diagram of the MEL model is shown in Fig. 7. Its typical data is given in Appendix.

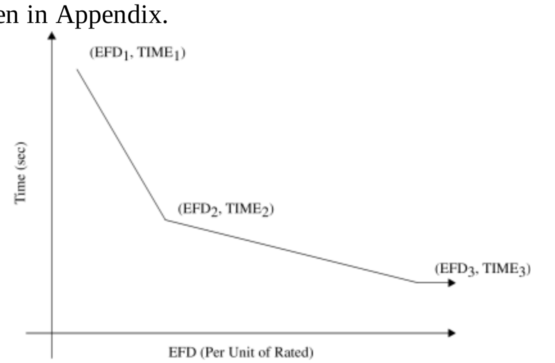

Fig. 6. Inverse Time Characteristics of Maximum Excitation Limiters

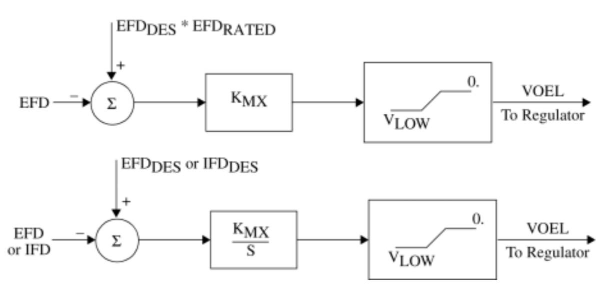

Fig. 7. Block Diagram of Maximum Excitation Limiters

The self-restoration model (EXTLD) simulates the general effects of loads being reset to a constant MW and constant Mvar in the steady state without specifically modeling the equipment responsible for this resetting. Fig. 8 shows the load reset model block diagram [4]. Its typical data is given in Appendix.

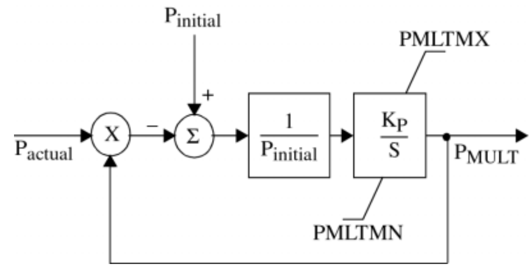

Fig. 8. Block Diagram of Load Reset Model

For comparison, other load models may also be simulated. Examples are:

(a) 50% constant current and 50% constant impedance with voltage dependence modeled
(b) 50% constant MVA and 50% constant current with voltage dependence modeled
(c) complex load model

The complex load (CLOAD) model represents a composite load of induction motors, lighting and other types of equipment such as would be fed from many typical substations. This model also simulates the response of loads to changes in voltage and frequency. The model represents effects that are significant for the initial period following a disturbance (the usual transient stability period), long term effects, and the transition between the two. The structure and block diagram of the CLOAD model is given in Appendix [5].

III. Case Studies

The analytical tools and models described in the previous section were applied to the ESB National Grid system. The subsequent sections present system background, case studies and results.

A. National Grid System

The National Grid transmission network has over 5,800 km of lines and cables throughout Ireland. It operates at 110kV, 220kV and 400kV. The 400kV network consists of two feeds from a major generating station on the West coast to the largest load center in Dublin, on the East Coast. The 220kV network forms the backbone of the transmission network while the 110kV network acts as both a transmission and sub-transmission network depending on location.

The National Grid has a peak demand of 3,800 MW and annual generation of 22,000 GWh. There are over 60 installed generators on the ESB system, although generally at most 40 units are needed on-line together. They comprise a variety of fuels: coal, heavy fuel oil, gas and peat. A wide range of generation technologies mirrors the variety of fuels: conventional thermal/steam, open-cycle combustion turbine (OCCT), combined-cycle combustion turbine (CCGT), hydro and pumped storage stations. There is no automatic generator control and unit set points are determined by operator action from the National Control Center.

In 1995 ESB reconnected with Northern Ireland Electricity (NIE) services, at 275kV, making the current combined system peak load 5,300 MW. This increased the number of generators that responded to MW imbalances and also increased total system inertia. This has reduced the level to which system frequency falls after any given generator contingency. In comparison, in the mid-1980s, the largest on-line sets were 305 MW coal-fired thermal units, which remain the largest units today, represented up to 40% of total generation in periods of low system load.

B. AC Contingency Analysis Results

The TPLAN model was applied to the ESB system to search the steady-state voltage problems for a base case load flow and three generation scenarios representing potential voltage collapse situations. This included extensive n-1/n-2 contingency tests. Voltage operating criteria were specified as 0.9~1.1pu during the contingency tests. Among the contingencies tested, eleven critical contingencies were found. These contingencies caused either a wide area of low voltages or voltage collapse. Table 1 lists the results of contingency analysis.

C. OPF Results, P-V and Q-V Curves

The voltage problems shown in Table 1 can be solved by adding shunt reactive compensation. The OPF model was applied to the system to find the best location and the least amount of such shunts. Table 2 gives the OPF results. It was assumed that these shunts were to be placed at 110 kV substations. This table summarizes additional Mvars required, or reactive margin for each critical case in Table 1. It indicates relative severity of the critical contingencies, i.e., the more shunt compensation is required, the more severe the contingency is. For example, contingency #9 needs the largest amount of compensation (78 Mvar), and hence it represents the worst contingency.

For comparison with the OPF results, P-V and Q-V curves were also generated from a series of post-contingency flows. Due to limited space, only Q-V curves are discussed here. Both the system and capacitor Q-V curves were calculated for the stations that require the largest amount of shunt compensation. For illustrative purpose, only the Q-V curve for contingency #1 is plotted and shown in Fig. 9. This plot shows both the system and capacitor curves at a 110 kV station. The bottom of the system Q-V curve, also called 'knee' point, where the derivative dQ/dV is equal to zero, represents a voltage stability limit. Relative to the knee point, operation on the right side of the Q-V curve is stable as an increase in Q is always accompanied by an increase in V. The knee point also defines the minimum reactive power requirement for stable operation. On the other hand, there are five capacitor Q-V curves in the plot. The intersection between the capacitor and the system Q-V curves establishes a steady-state operating point. As seen in Table 2, OPF determines that additional 28 Mvar will be required at this station. In Fig. 8, the intersection between the 30 MVAR capacitor Q-V curve (second lowest one) and the system Q-V curve gives coordinates (1.0pu, 28 MVAR). This point represents the voltage and additional compensation at the same station, which is consistent with the OPF value.

D. Long Term Dynamic Simulation

Six worst contingencies in Table 2 were selected for voltage stability simulations in time domain. These long term dynamic simulations mainly investigated the impact of slower speed controls and variations in load models. The disturbance included a three-phase fault applied to a 220kV station and cleared after 0.1 second with the outage of two circuits. A 120-second simulation was performed to capture most of the voltage-related response of the system.

TABLE 1~~1~~ SUMMARY OF N-1/N-2 CONTINGENCY ANALYSIS WITH THE ESB SYSTEM
(L.V. = LOW VOLTAGE V.C. = VOLTAGE COLLAPSE, BLANK FIELDS = NO VOLTAGE PROBLEMS)

Cont #	Line and/or Generator Outages (From or To or Generator Bus No., kV, Circuit ID)	Voltage Problems			
		Base Case	Scenario 1	Scenario 2	Scenario 3
1	From 642 220 kV To 4522 220 kV Ckt 1	L.V.		L.V.	L.V.
2	From 1641 110 kV To 1642 220 kV Ckt 1	L.V.	L.V.	L.V.	L.V.
3	From 1661 110 kV To 2781 110 kV Ckt 1		L.V.	L.V.	V.C.
4	From 2562 220 kV To 4242 220 kV Ckt 1				L.V.
5	From 2521 110 kV To 2522 220 kV Ckt 1				L.V.
6	From 2521 110 kV To 4981 110 kV Ckt 1				L.V.
7	From 4041 110 kV To 4981 110 kV Ckt 1				V.C.
8	Generator 39672 10.0 kV Generator 39677 9.60 kV From 3202 220 kV To 4722 220 kV Ckt 1			L.V.	
9	From 5141 110 kV To 5142 220 kV Ckt 2 From 5141 110 kV To 5142 220 kV Ckt 1			L.V.	
10	From 1642 220 kV To 4522 220 kV Ckt 1 Generator 35073 9.60 kV	L.V.	L.V.	L.V.	V.C.
11	From 2521 110 kV To 2522 220 kV Ckt 1 From 2521 110 kV To 3501 110 kV Ckt 1	L.V.	V.C.	L.V.	L.V.

TABLE 2 SUMMARY OF OPF ANALYSIS WITH THE ESB SYSTEM

Critical Cont #	Worst Scenario	Additional Total Shunts	Worst Cont #
1	Scenario 3	28 MVAR	4
2	Scenario 3	26 MVAR	5
3	Scenario 1	13 MVAR	8
4	Scenario 3	2 MVAR	11
5	Scenario 3	13 MVAR	9
6	Scenario 3	18 MVAR	7
7	Scenario 3	23 MVAR	6
8	Scenario 2	10 MVAR	10
9	Scenario 2	78 MVAR	1
10	Scenario 3	49 MVAR	2
11	Scenario 1	40 MVAR	3

For comparison, the ESB transient stability model, referred to as the ESB default model, was also simulated. This model includes load voltage-dependence effects and defines 50% constant current and 50% impedance for real power component, and 100% constant impedance for reactive power component. Again, for illustrative purpose, only one case is discussed here. Fig. 10 shows dynamic response of the voltage at a 220 kV station for various load models. It can be seen from the figure that different load models affect the voltage following the disturbance. OLTC moves to control the voltage at the station in about 35 seconds during the dynamic process. In the meantime, the station voltages start dropping at about 35 seconds. This is because some generators are now operating with their vars exceeding the limits. In such cases, The MEL equipment starts ramping down the excitation field voltages in accordance with their design. The generator terminal voltage is no longer being regulated and therefore starts dropping. As the voltage is ramped down, the generator vars decrease.

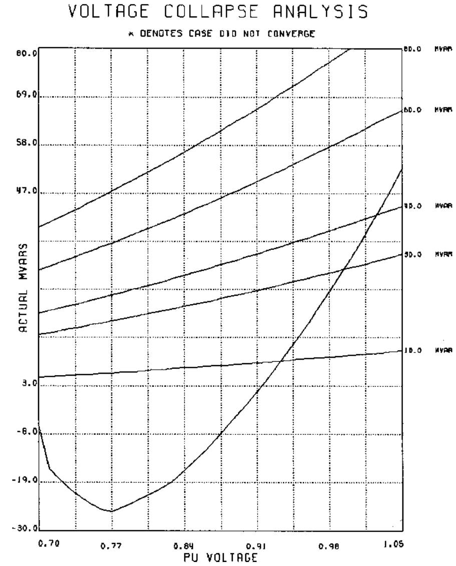

Fig. 9. Q-V Curve for a 110 kV substation

On the other hand, the ESB default model gives optimistic results. It can also be observed that the CLOAD model reduces the system voltage significantly because it models a large percentage of induction motors and the reactive power demand on the generators is high. In addition, the constant MVA and EXTLD load models require more reactive power from the system than the constant impedance load model and ESB default model, thus resulting in lower voltages.

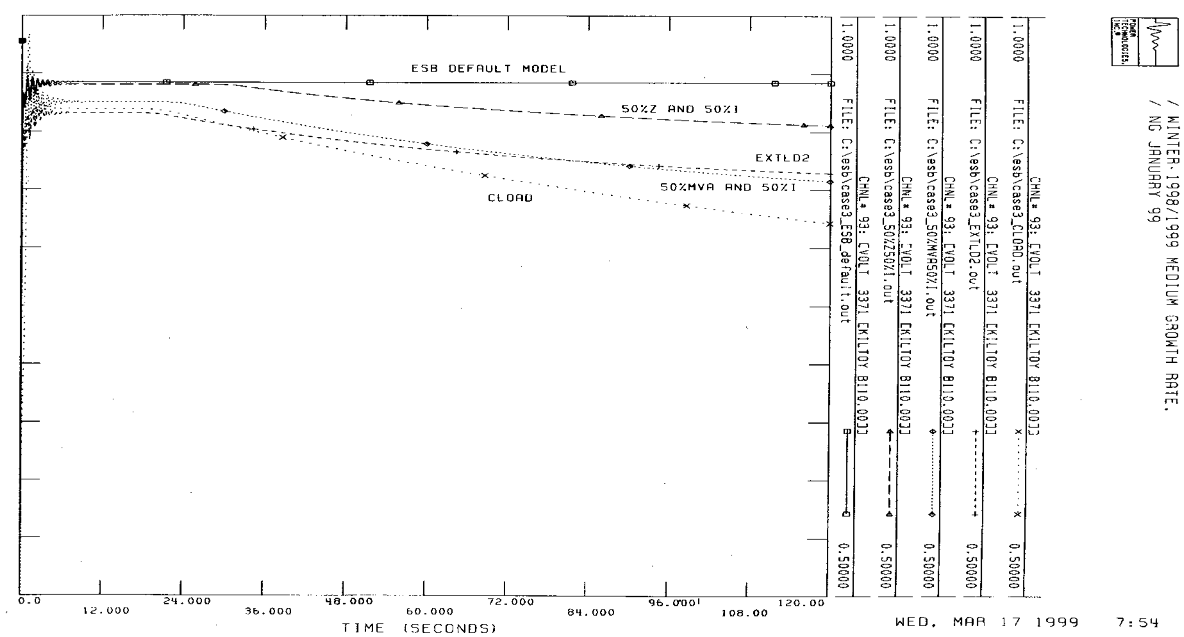

Fig. 10. Dynamic Response of Voltage (pu) at a 110 kV Station for Various Load Models

IV. Conclusions

Voltage stability assessment requires a set of advanced analytical tools and methods that are, in many ways, distinct from those used to study thermal capacity or angular stability. These methods include Q-V curves, P-V curves, OPF, AC contingency analysis and long term dynamic simulation. This paper used these tools to analyze the voltage stability of the ESB system. In the steady-state analysis, the voltage problems were quickly identified through contingency analysis. These problems were further investigated using OPF, P-V and Q-V curves and finally verified by long term dynamic simulations. In the simulations, slow controls such as on-line tap changers and maximum excitation limiters act to respond to the disturbance. Load characteristics are significant in the simulation of voltage stability. It is noted that the load model used for transient stability simulation may not be adequate for voltage stability assessment. In general, constant power model and dynamic load model such as induction motors have an important effect on voltage stability. In the simulations, various load models were compared to show different effects.

It is also noted that, in general, the steady-state analysis presents the conservative (worst) results, while the dynamic results depend largely on the modeling of loads. Therefore, a more detailed model for loads (in particular for motors) may be required in the voltage stability studies. The study serves as a reference for operators in analyzing similar contingencies to obtain a better indication of the load model.

V. Appendix

A. Typical Data of Maximum Excitation Limiters Model (Figs. 6 &7)

TIME1=120 s EFD1=1.1p.u.
TIME2=40 s EFD2=1.2p.u.
TIME3=15 s EFD3=1.5p.u.
KMX=0.01

B. Typical Data of Load Reset Model(Fig. 8)

KP=1.0 PMLTMX=1.1 PMLTMN=0.0

C. Complex Load Model and Typical Data

Referring to Fig. A1, the following values are assumed:
Large motors=30% Small motors=40%
Transformer exciting current=1.0%
Discharging lighting=10%
Constant Power=9%; KP=1

VI. Acknowledgment

The authors gratefully acknowledge the discussions of Mr. R. J. Koessler, formerly of PTI, and Mr. J. W. Feltes in performing the above studies.

VII. References

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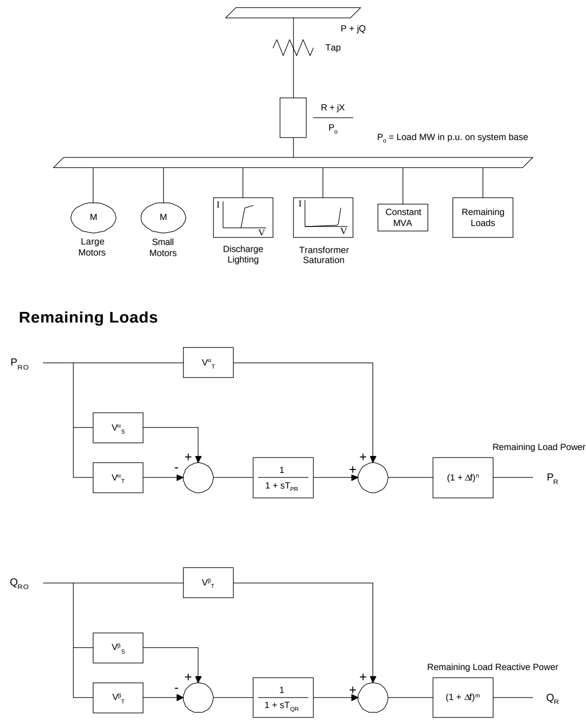

Fig. A1. Block Diagram of Complex Load Model

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VIII. Biographies

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Michael Power received his B.E. and M.Eng.Sc degrees in Electronic Engineering from University College Dublin in 1977 and 1979. Since then he has been working with the Electricity Supply Board of Ireland. He has worked on EMS and other control center projects. He is currently Manager, Power System Control and has interests in power system operation, SCADA and voltage collapse. He is currently convenor of CIGRE Working Group 39.01, Control Center Performance.