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VOLTAGE STABILITY ANALYSIS OF GRID CONNECTED EMBEDDED GENERATORS

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Abstract

The increasing costs and stringent environmental regulations are making the construction of large power stations to meet rising energy demands economically unfeasible. Hence, Embedded Generation (EG) is predicted to play a prominent role in the electric power systems of the future. The term "embedded generation" refers to electricity generation connected at distribution level rather than transmission level. The insertion of EGs presents a new set of conditions to distribution networks. The aim of this paper is to conduct a voltage stability analysis using an iterative power system simulation package, PowerWorld^{TM} Simulator, to evaluate the impact of strategically placed EG on distribution systems with respect to the critical voltage variations and collapse margins. This paper concludes with the discussion of EGs' excellent options for system reactive power compensation and voltage stability.

1. INTRODUCTION

In the last decade, environmental issues and concerns have increasingly come to the forefront. One area that attracts greatest environmental concern is energy use. Energy conservation policies in several countries encourage the use of renewable energy or so called "green energy" sources such as wind, hydro, solar and biomass. In Australia, for example, a mandatory renewable energy target has been imposed. The Renewable Energy (Electricity) Act 2000 requires the generation of 9500 GWh of extra renewable electricity per year by 2010 [1].

To date, 6% of Australia's total energy use comes from renewable energy sources. As of January 2002, there are 270 operating renewable energy power stations in Australia with biomass being the largest source of renewable energy [1]. In the electricity sector, current use of renewable energy contributes approximately 10.7%, most of which is generated from large-scale Hydro electricity schemes [1].

Embedded generation (EG) has the potential to promote the extensive use of renewable sources. The term "embedded generation" refers to electricity generation connected at distribution level rather than transmission level [2]. EG can reduce the effect of losses while providing reactive power and contingency reserves to the network. It can also reduce the need for new transmission and distribution facilities consequently reducing overall infrastructure costs.

For more than 50 years, modern electrical power systems have conventionally transmitted power from HV to LV and are generally designed to operate without any electricity generation on the distribution system or customer loads [3]. The introduction of EGs can significantly impact the flow of power and voltage conditions at consumers and utility equipment. The impacts may either manifest themselves positively or negatively depending on the distribution operating characteristics and the EG itself.

To gain lucrative benefits, EG sources must be reliable, dispatchable, of the proper size and at the proper locations. Since many EGs will not be utility owned or will be of variable energy sources such as wind and solar, there is no guarantee that the above-mentioned conditions will be satisfied [2].

This paper commences with an overview of renewable energy and the important role of EG to promote the greater use of renewable sources. This is followed by a comprehensive description of the adopted methodology and the test systems used for the analysis. The results from the performed studies and simulations are discussed in detail. Finally, the paper will conclude with the summary of findings and provide relevant recommendations for future development in this area of research.

2. BACKGROUND

2.1 Objective

The objective of this study was to conduct a power system analysis using an iterative power system simulation package, PowerWorld^{TM} Simulator, to evaluate the impact of strategically placed EG on distribution systems with respect to the critical voltage variations and collapse margins.

2.2 Generation Technologies

Various technologies are used for generating electricity from other forms of energy. These generation technologies can be group as follows:

a) Rotating machine coupled to Synchronous AC Generators.
b) Rotating machines coupled to Induction Generators.
c) DC current sources coupled to Electronic Inverter Systems.

The type of generation technology adopted determines the behaviour of EG in a distribution system. The major difference between the synchronous generator and the induction generator is that the induction generator can only operate on the circular locus and so there is always be a defined relationship between real power (P) and reactive power (Q). Hence, the independent control of Power Factor in an induction generator is not possible [2]. This independent control of P and Q make synchronous generators attractive for embedded generation schemes. Electronic Inverter Systems, however, introduce power quality problems into the system [4].

2.3 Voltage Stability

A system experiences a state of voltage instability when there is a progressive or uncontrollable drop in voltage magnitude after a disturbance, increase in load demand or change in operating condition [5]. The main factor, which causes these unacceptable voltage profiles, is the inability of the distribution system to meet the demand for reactive power.

Under normal operating conditions, the bus voltage magnitude (V) increases as Q injected at the same bus is increased. However, when V of any one of the system's buses decreases with the increase in Q for that same bus, the system is said to be unstable [5].

Although the voltage instability is a localised problem, its impact on the system can be wide spread as it depends on the relationship between transmitted P, injected Q and receiving end V. These relationships play an important role in the stability analysis and can be displayed graphically.

2.3.1 PV Curves

When considering voltage stability, the relationship between transmitted P and receiving end V is of interest. The voltage stability analysis process involves the transfer of P from one region of a system to another, and monitoring the effects to the system voltages, V. This type of analysis is commonly referred to as a PV study [5].

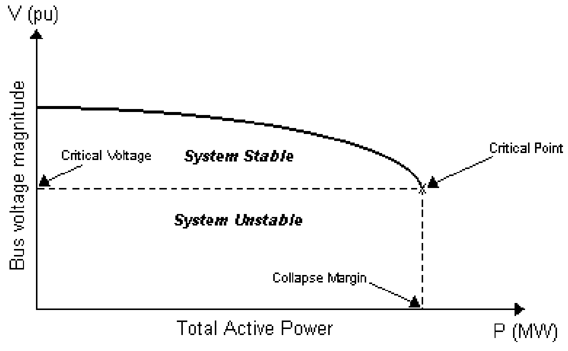

Fig. 1. Typical Power-Voltage (PV) characteristic curve

The Figure 1 shows a typical PV curve. It represents the variation in voltage at a particular bus as a function of the total active power supplied to loads or sinking areas. It can be seen that at the "knee" of the PV curve, the voltage drops rapidly when there is an increase in the load demand. Load-flow solutions do not converge beyond this point, which indicates that the system has become unstable. This point is called the Critical point. Hence, the curve can be used to determine the system's critical operating voltage and collapse margin. Generally, operating points above the critical point signifies a stable system. If the operating points are below the critical point, the system is diagnosed to be in an unstable condition [5].

2.3.2 QV Curves

Voltage stability depends on how the variations in Q and P affect the voltages at the load buses. The influence of reactive power characteristics of devices at the receiving end (loads or compensating devices) is more apparent in a QV relationship. It shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions [5]. Figure 2 shows a typical QV curve, which is usually generated by a series of load-flow solutions. Figure 2 shows a voltage stability limit at the point where the derivative *dQ/dV* is zero. This point also defines the minimum reactive power requirement for a stable operation [5].

An increase in Q will result an increase in voltage during normal operating conditions. Hence, if the operating point is on the right side of the curve, the system is said to be stable. Conversely, operating points in the left side of the graph are deemed to be unstable.

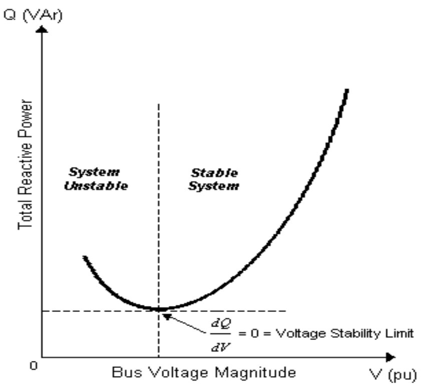

Fig. 2. Typical Reactive Power-Voltage (QV) characteristic Curve

2.4 Impacts of EG

Connecting a generation scheme to a distribution network will affect the operation and performance of the network depending on the scheme and rating of the generator itself [6]. The impacts are as follows:

2.4.1 Power Flows

The significant penetration of embedded generation reverses the power flow and the network is no longer a passive circuit supplying loads. It becomes an active system with power flows and voltages determined by the generation as well as the loads [7]. In these cases, the generator exports excessive power to all the loads on the system to which it is connected. The surplus power is transferred into a higher voltage system.

2.4.2 Network Losses

EG will have an impact on losses in a network. The strategic placement of EG on the network can reduce losses normally seen by the system while improper placement may actually increase the network losses [8]. Proper placement can also free available capacity for transmission of power and reduce equipment stress. Siting of EGs to minimise losses is like siting capacitor banks for loss reduction. The only difference is that EG will impact both real power and reactive power flow, whereas capacitors only impact the reactive power flow. A small penetration of a strategically placed EG with an output of just 10-20% of the feeder demand can have a significant loss reduction benefit for the system [8].

2.4.3 Steady Sate Voltage Variations

For networks where X>>R, the bus voltage magnitude increases as reactive power at the same bus is increased. If an adjacent load absorbs the output from an embedded generator, then the impact on the distribution network voltage is likely to be advantageous. However, if it is necessary to transmit the power through the network then steady-state voltage variations may adversely become excessive [9].

3. APPROACH AND METHODOLOGY

The system study was evaluated through a series of scenarios comprising of different system loads, operating modes of EGs, interconnection schemes and location of EGs.

3.1 Simulation Software

The PowerWorld^{TM} Simulator (Simulator) package Ver 8.0 is able to perform Load Flow simulations using Newton-Raphson power flow algorithm and is capable of analysing multiple sources on the distribution system, predicting the network voltages, voltage stability and losses. This makes it suitable to study the behaviour of a system with EG

Simulator's voltage stability assessment tool, PV-QV, can be used to analyse the voltage characteristics of a system. The PVQV tool allows the user to monitor any system parameter while automatically increasing a user-defined transfer. It can solve multiple load flow solutions in order to generate PV curves for a particular transfer or a QV curve at a given bus [10].

3.2 Test Systems

Many studies have been conducted on EG connected to 11kV networks and have published several results. However, very little studies have been conducted on the reticulation regions. This paper will present the impact of EGs when interconnected in the reticulation regions.

The three distribution systems were chosen to study the impact of EGs. The 5 Bus system was adopted from IEE Power and Energy Series 31. It was used to demonstrate the effects of EG and to understand the concept of embedded generation. The IEEE 13 Bus system, rated at 4.16kV, is very small and yet displays some very interesting characteristics. Lastly, the IEEE 37 Bus system, rated at 4.80kV, is a three-wire delta system, which was modelled from an actual feeder located in California [11].

3.3 Locating EGs

The impact of feeder losses of EGs can be analysed with the rule of thumb, "2/3 Rule" often used in capacitor placement studies in distribution systems. The rule states that, *"For a feeder with a uniform KVAr load, the best capacitor size is 2/3 of the KVAr load, located 2/3 of the distance out the feeder*."[12]. Figure 3 illustrates the effect of the 2/3 Rule on the power flow and the reduction in losses.

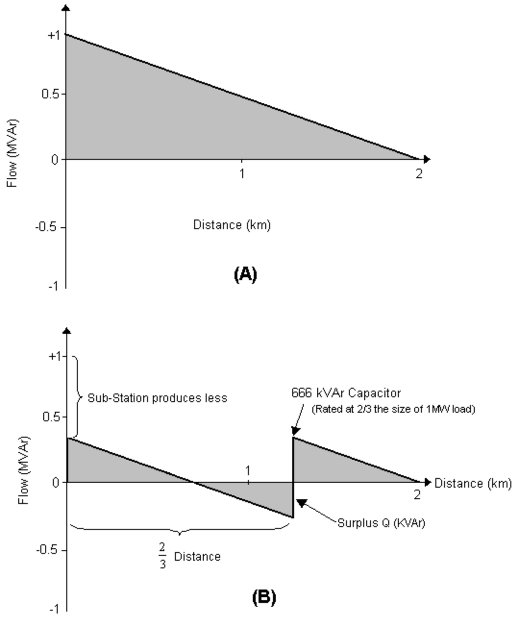

Fig. 3. Graphical display of the 2/3 Capacitor Rule [12].

As shown in (B) of Figure 3, the substation produces less Q as the capacitor produces the required Q as opposed to (A). Hence, from the sub-station point of view, there is reduction in power loss. This is due to the fact that power loss is proportional to the amount of power produced for given impedance of a transmission line.

Similarly, the same graphical and rule-of-thumb depiction can be applied to EGs and its impact will be similar to that of a capacitor. However, it must be noted that the 2/3 Rule is only an approximate, which provides a useful guide to the placement of EGs [12].

3.4 Implementation of Feeders

As described above, the location of the EG depends on the feeder's length. A feeder will be located in the Load Concentration Zone (LCZ) supplied from the transmission grid. The feeder will be modelled as a transmission line, which is connected from the transmission grid to the selected loads, within the LCZ. This arrangement was chosen based on the size of the loads connected in a particular region of the LCZ. The aim is to group the large loads into a feeder so that the penetration of the EG could show significant effects. Two feeders were chosen to compare the effects of EG network losses according to the 2/3 Rule. It is important to note that this implementation only applies to the IEEE 13 Bus and IEEE 37 Bus systems.

Feeder 1 from the IEEE 13 Bus system is from Bus 650 to Bus 652. The feeder is 1.55km long. Feeder 2 is from Bus 650 to Bus 675. The feeder is 1.37km long. Feeder 1 from the IEEE 37 Bus system is from Bus 799 to Bus 741. The feeder is 2.43km long. Feeder 2 is from Bus 799 to Bus 728. The feeder is 1.48km long. See Figure 4 and 5.

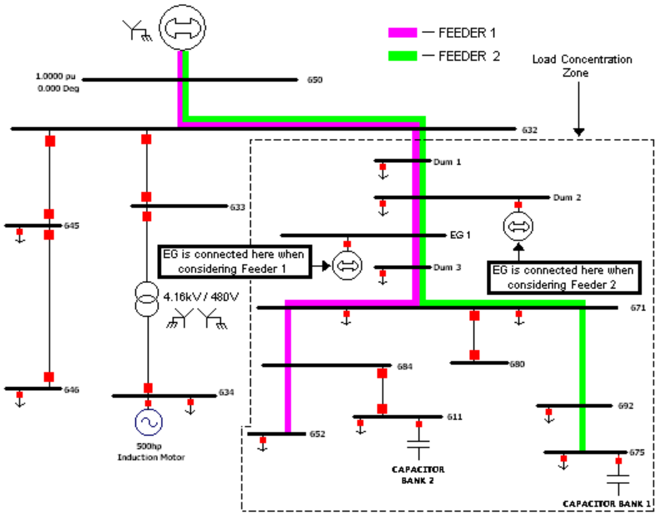

Fig. 4. Feeder implementation of IEEE 13 Bus System

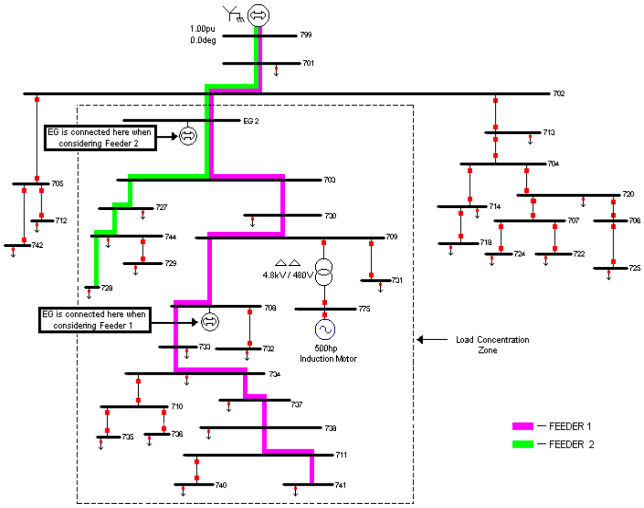

Fig. 5. Feeder implementation of IEEE 37 Bus System

3.5 EG input Parameters

Tables 1 lists the EG's input parameters. The 2/3 Rule applies only to the IEEE 13 Bus System and IEEE 37 Bus System.

Test Sys	*Loca-tion*	*Base MVA*	*Unity Power Factor*		*0.95 Lagging Power factor*		*0.95 Leading Power Factor*	
			P (MW)	*Q (MVAr)*	*P (MW)*	*Q (MVAr)*	*P (MW)*	*Q (MVAr)*
FEEDER 1								
IEE 5 Bus	Bus D	100	20.0	0.00	20.0	6.60	20.0	-6.60
IEEE 13 Bus	Bus EG1	10	3.51	0.00	3.51	1.15	3.51	-1.15
IEEE 37 Bus	Bus 708	10	1.15	0.00	1.15	0.38	1.15	-0.38
FEEDER 2								
IEE 5 Bus	-	100	-	-	-	-	-	-
IEEE 13 Bus	Bus Dum 2	10	5.64	0.00	5.64	1.85	5.64	-1.85
IEEE 37 Bus	Bus EG2	10	4.26	0.00	4.26	1.40	4.26	-1.40

Table 1. EG input parameters

4. RESULTS AND DISCUSSIONS

The results presented are system specific and are accompanied by discussions of the observations made.

4.1 IEE 5 Bus System

Bus D was selected for evaluation as it a critical bus prone to voltage instability. Figure D shows the PV curve for the system when the EG is operated at different conditions; it represents the variation in voltage at Bus D as a function of total active power load.

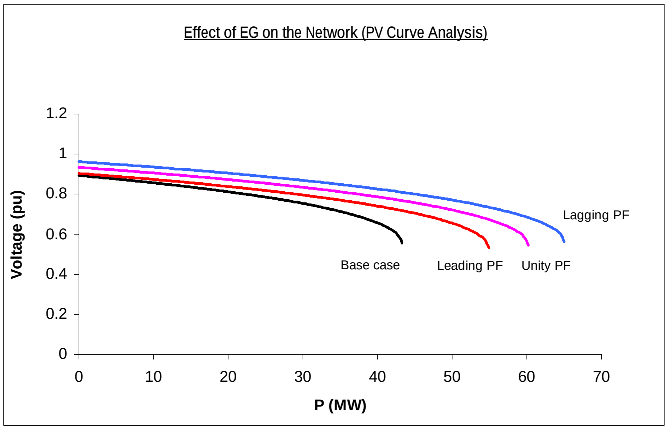

Fig. 6. PV Curve Analysis of IEE 5 System.

Operating Condition	*Critical Voltage (pu)*	*Collapse MW*
Base Case	0.556	43.3
Unity PF	0.546	60.2
0.95 Lagging PF	0.565	65.0
0.95 Leading PF	0.533	54.9

Table 2. PV Curve Result summary for IEE 5 Bus System

It can be seen that the EG has improved the system's collapse margin particularly when the EG is operated at Lagging PF. The Collapse Margin in improved by 50.12%. This means that the system becomes less vulnerable to voltage collapse by 50.12%.

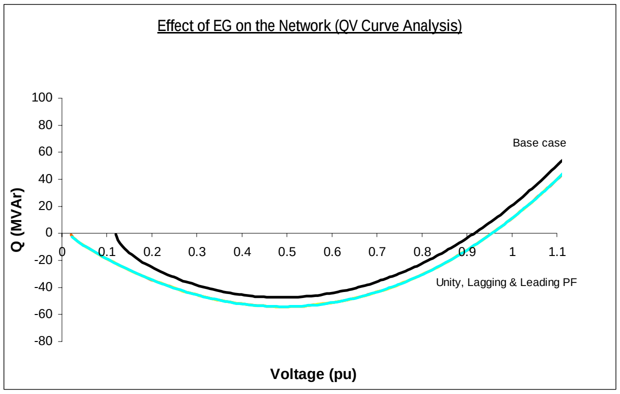

Fig.7. QV Curve Analysis of IEE 5 System

Operating Condition	Critical Voltage (pu)	Minimum MVAr
Base Case	0.4941	47.4
Unity PF	0.4944	54.2
0.95 Lagging PF	0.5026	54.2
0.95 Leading PF	0.4044	54.2

Table 3. QV Curve Result summary for IEE 5 Bus System

It can be seen that the EG has improved the system's stability limit regardless of its operation mode. The Stability Margin is improved by 14.35%. This means that the minimum reactive power requirement for stable operation has been lowered by 14.35%. It must be noted that the smaller the margin, the closer the system is in operating near the Critical Operating Point.

4.2 IEEE 13 Bus System

As mentioned in Section III, the 2/3 rule and the simulation parameters were applied to system. Like the IEE 5 Bus system, the EG was found to improve the system's voltage stability. Bus 684 was selected for evaluation due to its location within the Load Concentration Zone and is supplied by a heavily loaded Bus 671.

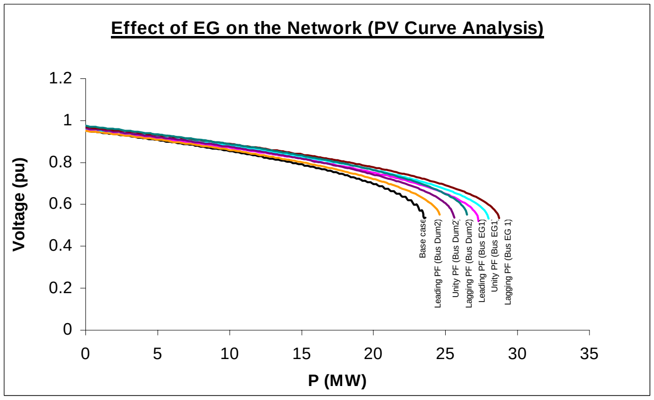

Fig.8. PV Curve Analysis of IEEE 13 System

Operating	*EG at Bus EG1*		*EG at Bus Dum 2*	
	Critical Voltage (pu)	*Collapse MW*	*Critical Voltage (pu)*	*Collapse MW*
Base Case (No EG)	0.537	23.6	-	-
Unity PF	0.532	28.0	0.537	25.6
0.95 Lagging PF	0.550	28.6	0.555	28.6
0.95 Leading PF	0.547	24.6	0.550	24.6

Table 4. PV Curve Result summary for IEEE 13 Bus System

It can be seen that the EG has improved the system's collapse margin particularly when the EG is connected at Bus Dum2 and operated at Lagging PF. The Collapse Margin in improved by 21.19%. This means that the system becomes less vulnerable to voltage collapse by 21.19%.

Figure 9 shows the QV curves when the EG is connected at different locations and operated at various modes.

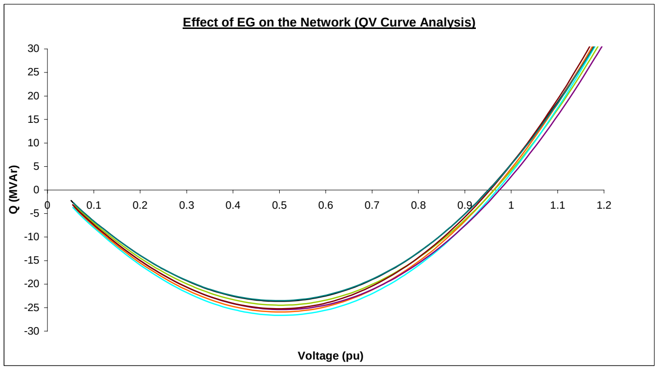

Fig.9. QV Curve Analysis of IEEE 13 Bus System

Operating Condition	*EG at Bus EG1*		*EG at Bus Dum 2*	
	Critical Voltage (pu)	*Minimum MVAr*	*Critical Voltage (pu)*	*Minimum MVAr*
Base Case (No EG)	0.5009	23.7	-	-
Unity PF	0.4121	25.9	0.5034	24.5
0.95 Lagging PF	0.4998	26.7	0.4948	25.4
0.95 Leading PF	0.5043	25.2	0.5115	23.5

Table 5. QV Curve Result summary for IEEE 13 Bus System

Hence, it can be seen that the EG has improved the system's stability limit when it is connected at Bus EG1 and operated at Unity PF. The Stability Margin in improved by 9.92%. This means that the minimum reactive power requirement for stable operation has been lowered by 9.92%.

4.3 IEEE 37 Bus System

The 2/3 Rule was applied to perform the system study. However, it must be noted that the system's load profile was modified to make the system "unhealthy". The spot loads were increased by a factor of five (500%) to create the "unhealthy" effect. The aim of this was to analyse the EG's ability to enhance the system stability margin under the unhealthy condition.

Bus 709 was selected for evaluation, due to its heavy loading and location within the LCZ. The tables below show the summary of results.

Operating Condition	EG at Bus 708		EG at Bus EG2	
	Critical Voltage (pu)	Collapse MW	Critical Voltage (pu)	Collapse MW
Base Case (No EG)	0.652	47.0	-	-
Unity PF	0.677	47.4	0.534	136.99
0.95 Lagging PF	0.677	47.4	0.540	136.99
0.95 Leading PF	0.682	47.0	0.539	135.70

Table 6. PV Curve Result summary for IEEE 37 Bus System

The system becomes less vulnerable to voltage collapse by 191.47% particularly when the EG is connected at Bus EG2 and operated at Lagging PF. This situation, however, is not likely to be implemented; as such a penetration into the Distribution system will cause the Utility to loose control of the Grid. The aim an EG is to complement a distribution network, not to control it.

Operating Condition	EG at Bus 708		EG at Bus EG2	
	Critical Voltage (pu)	Minimum MVAr	Critical Voltage (pu)	Minimum MVAr
Base Case (No EG)	0.9582	0	-	-
Unity PF	0.9631	0	0.9682	0
0.95 Lagging PF	0.9641	0	0.9699	0
0.95 Leading PF	0.9621	0	0.9665	0

Table 7. QV Curve Result summary for IEEE 37 Bus System

Table 7 indicated that the system was in a critical operating point due to its unhealthy condition. Bus 709 is already heavily loaded and the QV curves show that the system has a very small stability margin, which led to failure of the power flow convergence at the stability limit. The EG operated at various modes and connected at different locations the system's voltage collapse margin could not be enhanced. Hence, it proves that the EG cannot dramatically improve the system's stability limit when the system is in unhealthy condition. EG unit can only support the network.

5. CONCLUSIONS

This paper established some significant findings. The system analysis was conducted successfully and the results obtained are according to expectations. The system study demonstrated that the EG can have significant impacts on distribution system.

The significant finding of this thesis is the EG's ability to improve the voltage collapse margin. The IEEE 13 Bus system for example, had its collapse margin increased by 21.19%. This indicates that the system becomes less vulnerable to a collapse when subjected to a disturbance. The study showed that the strategically placed EG was able to increase the stability margin by increasing the stability limit threshold. However, this does not apply to all systems as the system loads play a major role in this aspect. From the IEEE 37 Bus system, it was discovered that the EG does have the capability to enhance the characteristics of an unhealthy system. The EG unit was able to give minimal improvements as the system itself was heavily loaded. Therefore, the EG cannot be applied in these situations as it is meant to support a network rather than control it.

In summary, EGs operated at appropriate modes can offer excellent options for system reactive power compensation; voltage support and collapse margin enhancement provided it is of the proper capacity and at the proper location.

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