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### Energy injection by distributed generation for improvement in feeder-voltage profile

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# Energy Injection by Distributed Generation for Improvement in Feeder Voltage Profile

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## Abstract

A system with Distributed Generation (DG) has greater load carrying capacity and can support peak-shaving. A network with DG can correct for a poor voltage profile during peak loading. This paper addresses the loading patterns of rural feeders and the relative effectiveness of real and reactive injection to support feeder voltage profile. In this paper, real and reactive injection on a rural network has been investigated and the minimum required energy for voltage specification estimated. For the same voltage specification, distributed generation with real and reactive injection (DG-PQ) using Q priority (DG-QPQ) can drastically reduce fuel and energy requirements compared to the amount required by proportional use of real and reactive power in DG-PQ.

## 1.0 Introduction

In the early 1950s, there was a strong push for electrical network expansion in rural areas to provide electricity for agricultural and communities. Because of the small loads and loads spreaded over a wide area, the return on capital investment would be taking a long time, and therefore, a network was demanded that would be economical to construct and maintain in these areas. As a result, Single Wire Earth Return (SWER) systems have been constructed in most of the Australian rural areas. At very beginning, the loads connected to the SWER feeders were small. As load growth continues, some SWER systems have been reaching their technical capability. And with customers keenly aware of supply quality, customer complaints have been increasing. Over the years, load growth has begun creating problems for some existing SWER systems. One of the key problems is a wide voltage variation along the SWER feeders. The solution to this problem is to construct a new 22-kV or 33-kV three-phase backbone line or to augment the existing three-phase system through the areas where demand is high, redesigning the existing SWER systems into several smaller systems continued by the new feeders [1]. This solution may be technically effective but it can be expensive, especially for the areas where the rates of load growth are not sufficient to justify capital investment on a three-phase line. Distributed generation (DG) solution is an alternative to solve this type of problem in rural areas, which is less expensive, and defers the network augmentation to a time by which the demands will become sufficiently high to justify capital investment for augmentation. Since the rates of rural load growth are often small and increasing slowly, small size grid connected DG may be suitable in these places to satisfy consumers' demands and alleviate voltage variation by increasing and correcting voltage level in the network. Worldwide, the demand of DG installation in rural areas is growing very fast due to poor voltage and frequent blackout in these areas.

According to Ackermann et. al. [2], DG can be defined as an electric power source connected directly

to the distribution network or on the customer site of the meter. Sendberg [3] has shown how local energy systems can contribute to the conversion of today's energy systems to a sustainable state by identifying many different actors in the energy value chain and what roles they can play in the development towards sustainability. Salman [4] has investigated the impact of rotating type DGs on distribution network and formulated a definition of effective DG integration from the aspects of voltage regulation, protection and network disturbances. The authors in [5] have analysed the main protection techniques by connecting different generation units and identifying the operating conditions that lead the protection failing to detect isolation of generator site from utility supply. They have proposed some methods for improving reliability for situations which currently present difficulties in detection of island operation.

A particular line could be overloaded to a level requiring only reactive support for 2 hours per day but may only require the addition of real power for 40 min on the worst day. This aspect is investigated in this paper by examination of loading patterns of rural feeders and the relative effectiveness of real and reactive injection to determine the optimum allocation of resources to any real generation. An attempt has been made to estimate the minimum DG energy requirement for voltage specification with comparing the benefits of real and reactive power injections.

## 2.0 Loading Patterns of Rural Feeders

Load densities in a SWER distribution system are typically less than 0.5kVA/km of line with a maximum demand per customer of 3.5kVA [1]. A large system may supply up to 80 distribution transformers (or customers) with unit ratings of 5kVA, 10 kVA and 25kVA. The load patterns and demands vary greatly from customer to customer and from one season to another. Also, the length of SWER line varies according to customer distribution, with an average SWER feeder length of 60-km, although a 400-km SWER system is in operation in one state of Australia. Typically, conductors have a small diameter and high strength, and are made of aluminium/steel or steel

cable. These high impedance conductors in long SWER lines can cause the total impedance at the end of the feeder to be 1000 ohms for 19.6kV lines.

Fig.1 shows a Daily Load Curve (DLC) of a sample day for a typical SWER network in which maximum demand at peak-time is 504 kVA and the peak occurs approximately between 5p.m. to 8:30p.m. A synthetic daily load duration curve for a month is generated by scaling the standard day (shown in Fig.2) by a factor, which has a random component. Fig.3 shows the load demand in percentage of time and highlights the peak demand and percentage of time associated with the peak demand. From Fig.3 for this synthetic load it is seen that for 0.10% time the load demand is above 600kVA, 1.07% time above 550kVA, 3.75% time above 500kVA, 8.27% time above 450kVA, 14.20% time above 400kVA, 25.10% time above 350kVA, 44.90% time above 300kVA, 63.90% time above 250kVA, 85.25% time above 200kVA, 98.12% time above 150kVA and 100.00% time above 100kVA.

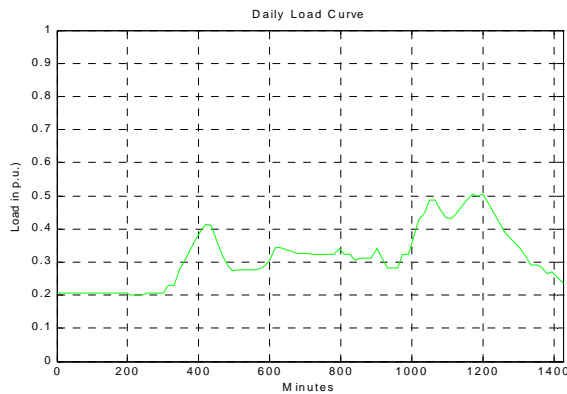


Fig.1: Daily Load Curve

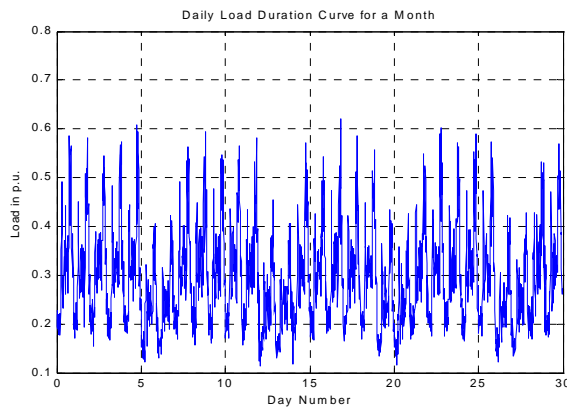


Fig.2: Daily load duration curves for a month

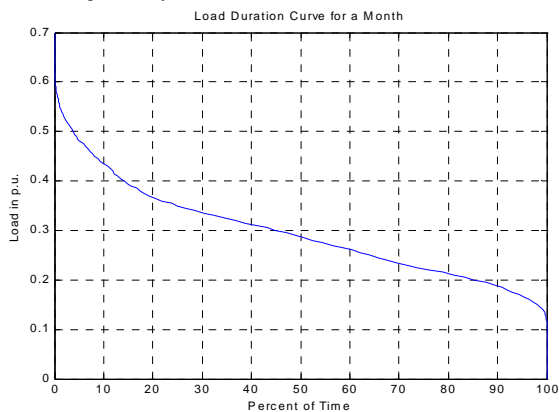


Fig.3: Load duration curve for a month

### 3.0 Voltage Conditions of Feeders with and without DG Inclusion

To investigate the voltage conditions and DG energy requirement to meet a voltage specification, the SWER system with a single DG discussed in [6] has been used as a test system for simulation. Minimum voltage conditions with daily and monthly load demands have been examined in the system with and without DG integration. Results are reported in the following sections. It is noted that the maximum allowable voltage rise or drop in SWER lines is 6%, and is used in the simulation as a hard limit for voltage controllers.

#### 3.1 Minimum Voltage in SWER System without DG Inclusion

The system without DG can support up to 381.2kVA load and thus cannot support the peak-time demand of the standard day. The voltage level goes below 0.94 p.u. for any demand above this in a standard day. Fig.4 shows daily minimum voltage profile without DG for the sample SWER system. It is seen that voltage falls below 0.94 p.u. for 5 hours and 10 minutes of the day.

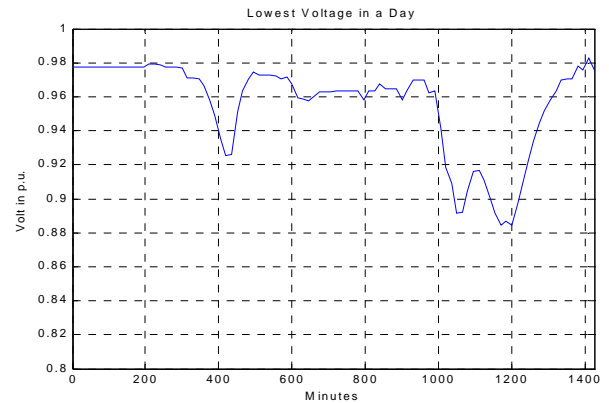


Fig.4: Lowest voltage based on daily load curve without DG

Minimum voltage and maximum demand of every day in a month are shown in Fig.5. Fig.5(a) shows lowest voltage in every day of a month for the monthly load demands. The lowest voltage profile in Fig.5(a) is reorganised in Fig.5(b) which represents minimum voltage duration curve. It is seen that for 5.45% of the time, voltage remains below 0.90 p.u., 10.31% time voltage is below 0.92p.u. and for 15.52% of the time, the voltage remains below 0.94p.u.

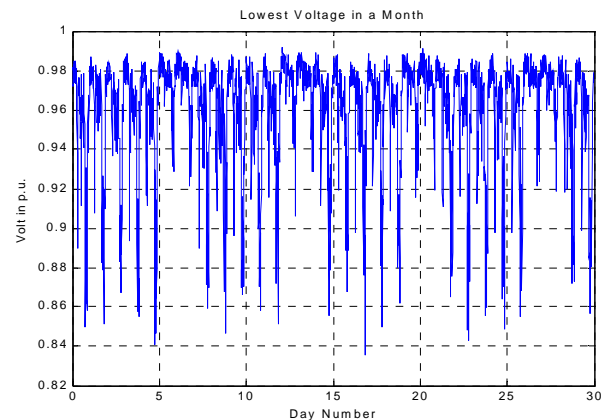


Fig.5(a): Lowest voltage profile for a month without DG

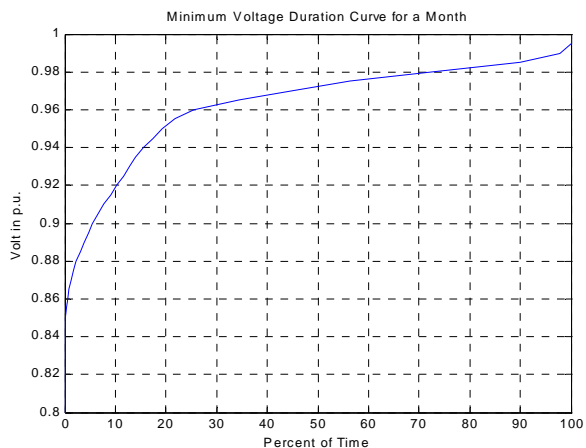


Fig.5(b): Lowest voltage duration curve for a month without DG

### 3.2 Minimum Voltage in SWER System with DG Inclusion

A DG of 100kVA is included in the SWER system to investigate the benefits from DG inclusion. DG can be operated in a real (DG-P), reactive (DG-Q) or real-reactive (DG-PQ) generation mode. However, DG-P will require large amount of fuel and hence the operating cost will be high. Therefore, DG-Q and DG-PQ are preferable from economic point of view. DG-Q and DG-PQ can be combined as DG-QPQ, which is the notation for DG-PQ with Q priority and generates only reactive power for low correction and as the load rises placing the reactive injection at the limit, the controller is activated to operate in the real-reactive (PQ) generation mode.

#### 3.2.1 Voltage Specification by DG-PQ

DG-PQ has been set to operate at the maximum voltage sensitivity of SWER lines with a voltage threshold or voltage reference of 0.95 p.u., that is, DG controller will be activated only if the connection point voltage is below 0.95 p.u. Fig.6(a) shows the power generation of DG-PQ at this condition. It is observed that DG-PQ has started the real and reactive power generation when the load level exceeds 368.7 kVA. The system with 100kVA DG can support up to 543.7kVA load without excessive voltage drop, after which the voltage in the system falls below the specified 6%. Fig.6(b) shows the minimum voltage and DG connection voltage profile for a standard day.

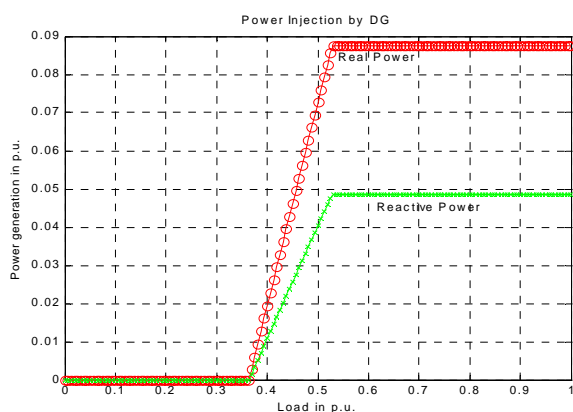


Fig.6(a): Power generation by DG-PQ (0.95 p.u. voltage threshold)

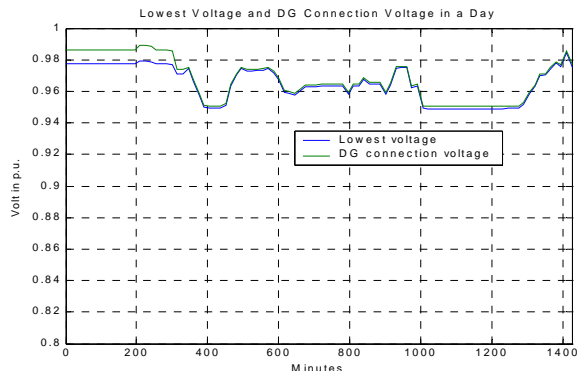


Fig.6(b): Lowest voltage and DG connection voltage with DG-PQ (0.95 p.u. voltage threshold)

Fig.7 represents the voltage conditions and DG-PQ contribution for the monthly load demand. Fig.7(a) shows the minimum voltage duration curve for a month at the presence of DG-PQ. Fig.7(b) shows maximum demand and minimum voltage for every day of a month in the presence of DG-PQ. It is observed that at the weekend the customer demands are low and therefore DG does not generate at its maximum level.

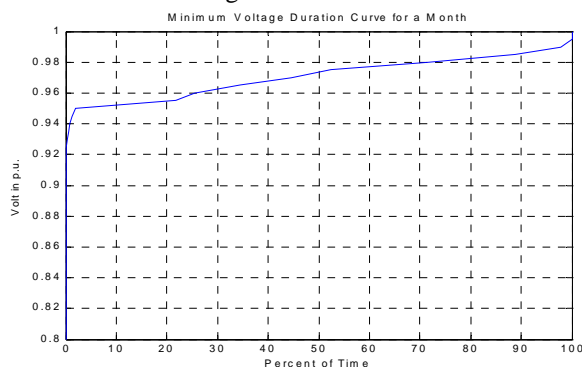


Fig.7(a): Minimum voltage duration curve for a month with DG-PQ (0.95 p.u. voltage threshold)

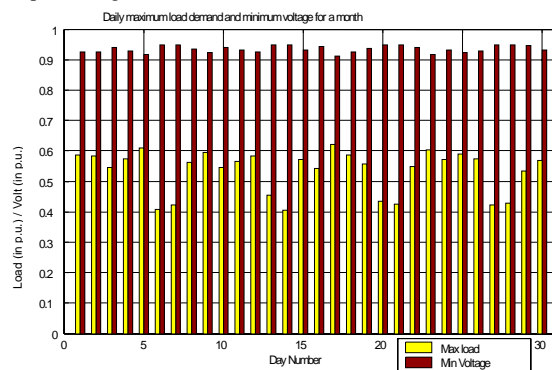


Fig.7(b): Daily maximum demand and minimum voltage for a month with DG-PQ (0.95 p.u. voltage threshold)

#### 3.2.2 Voltage Specification by DG-PQ with Q Priority (DQ-QPQ)

DG-QPQ, for low loads/demands, uses only the reactive power generation mode. This is because reactive generation is almost free of operational cost and it can meet the voltage specification for low and medium load demand. During the peak-time, it may not have sufficient capacity to raise the voltage level above the margin and therefore at that time the DG needs to be operated in the mode of real-reactive power generation and the P / Q ratio will be aligned with the ratio of maximum voltage sensitivity of the lines.

When the minimum voltage at the system becomes less than 0.94 p.u., the DG controller will activate and turn the DG mode from DG-Q to DG-PQ. DG will operate only if the connection voltage of DG is below 0.95 p.u. Fig.8(a) shows the power generation of DG-QPQ. Without compromising the minimum voltage specification, the system with DG-QPQ can support up to 543.7kVA load, which is same as with DG-PQ. It is observed that DG-QPQ commences reactive power generation from a load level of 362.5 kVA and real power generation from 468.7 kVA. DG-QPQ has started its generation a step earlier than DG-PQ due to the automatic action of tap changers in SWER system. Fig.8(b) shows the minimum voltage and DG connection voltage profile for a standard day.

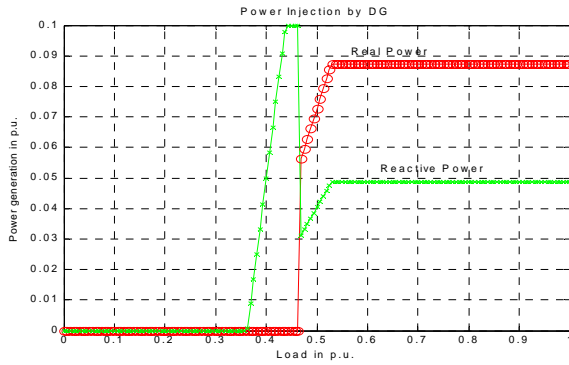


Fig.8(a): Power generation by DG-QPQ (0.95 p.u. voltage threshold)

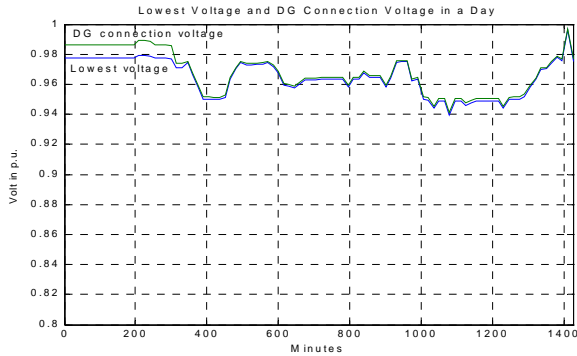


Fig.8(b): Lowest voltage and DG connection voltage with DG-QPQ (0.95 p.u. voltage threshold)

Voltage conditions with DG-QPQ contribution for load demand of a month are shown in Fig.9. Fig.9(a) shows lowest voltage in the SWER system and DG connection voltage in every day of a month at the presence of DG-QPQ. Minimum voltage duration curve for a month at the presence of DG-QPQ is shown in Fig.9(b).

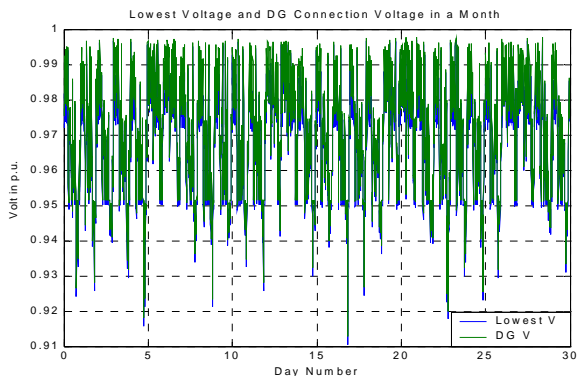


Fig.9(a): Lowest voltage and DG connection voltage with DG-QPQ (0.95 p.u. voltage threshold) for a month

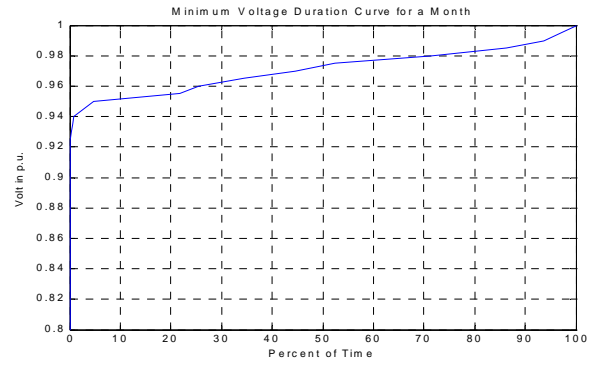


Fig.9(b): Minimum voltage duration curve for a month with DG-QPQ (0.95 p.u. voltage threshold)

Table 1 shows the load capacity and voltage conditions with and without DG. Here the DG is operated with 0.95 p.u. voltage threshold. From the table it is seen that lowest voltage in the SWER system is very low without DG. DG-QPQ exhibits marginally lower minimum voltage in the system for daily load demand than DG-PQ, as DG-QPQ generates reactive power and is not allowed to generate real power until the voltage level of the system goes below the lower margin. For the load demand of a month, voltage level of the SWER system without DG goes below 0.90 p.u. for 5.45% of time, 0.92 p.u. for 10.31% of time and 0.94 p.u. for 15.52% of time. Whereas, with the presence of DG, voltage does not go below 0.90 p.u., and less than 1% of time voltage is found below 0.94 p.u.

Table 1: Voltage level with and without DG

	Without DG	With DG-PQ (0.95p.u. threshold)	With DG-QPQ (0.95p.u. threshold)
Load Capacity	381.2 kVA	543.7 kVA	543.7 kVA
Minimum voltage in a standard day	0.8844 p.u.	0.9486 p.u.	0.9393 p.u.
Voltage below 0.90 p.u. in a month	5.4514 % of time	0.0000 % of time	0.0000 % of time
Voltage below 0.92 p.u. in a month	10.3125 % of time	0.0694 % of time	0.0694 % of time
Voltage below 0.94 p.u. in a month	15.5208 % of time	0.9028 % of time	0.9028 % of time

Voltage improvement of the system by DG-PQ and DG-QPQ has been examined with the operation of DG at voltage reference of 0.945p.u., 0.96p.u., 0.97p.u., 0.98p.u. and 0.99p.u. individually. It is observed that the transition of change of DG mode from Q operation to PQ of DG-QPQ is not smooth for a high threshold voltage. It can only be improved by paying a cost penalty on energy. To overcome this problem, the lower limit of voltage margin may be set closer to the threshold value for the operation of DG-QPQ. Therefore, the threshold value 0.95p.u. is a good choice for the operation of DG-QPQ, as it allows the tap changers to perform as much of the correction as possible and requires less DG energy and less fuel for DG operation. The following section discusses DG energy issues for voltage specification.

#### 4.0 Energy Estimation

The amount of energy contributed by DG depends on its mode of operation and voltage specification of the



system. No energy is transferred from DG to the system if DG generates only reactive power. This is due to the fact that energy is associated with real power and not with the reactive power. The Energy requirement is increased with the increase of voltage specification, as DG needs to generate more real power to meet the voltage requirement. The following sections estimate the daily and monthly DG energy and compared the benefits achieved from the operation of DG-PQ and DG-QPQ.

#### 4.1 Energy Estimation for DG-PQ

DG-PQ has been operated with the voltage threshold 0.95 p.u. and generates real and reactive powers simultaneously, at the proportion of voltage sensitivity of SWER lines. Fig.10(a) shows the real and reactive power generation and DG energy for a standard day. The amount of energy supplied by DG-PQ is 239.5 kW-hr in a standard day. Fig.10(b) shows the load demand and energy estimation in daily basis for a month. As the demand is low during weekend, the power generation and energy by DG-PQ are also low. The total energy contributed by DG-PQ in a month is 5794.3 kW-hr and the largest daily energy in the month is 301.5 kW-hr.

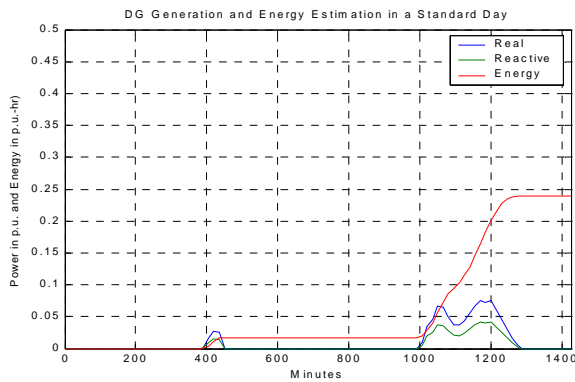


Fig.10(a): DG power generation and energy estimation for DG-PQ (0.95 p.u. voltage threshold) in a standard day

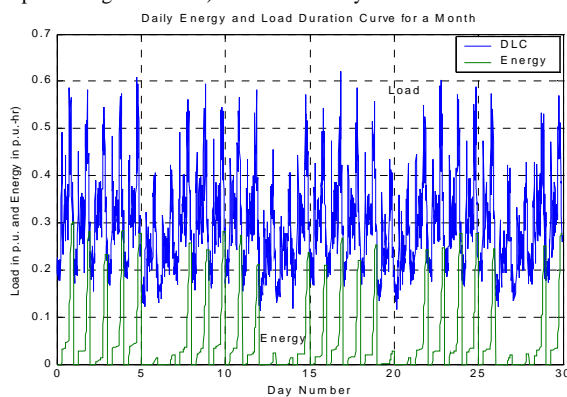


Fig.10(b): Daily load demand and DG energy for a month with DG-PQ (0.95 p.u. voltage threshold)

#### 4.2 Energy Estimation for DG-PQ with Q Priority (DG-QPQ)

DG-QPQ has been operated to generate power with the Q priority and voltage threshold of 0.95 p.u. It generates reactive power for low and medium load demand and supports the voltage. During the peak time, it turns to PQ mode and generates real and

reactive power in the same ratio as the voltage sensitivity of the lines. Fig.11(a) shows the real and reactive power generation by DG-QPQ and DG energy for a standard day. The amount of energy supplied by DG-QPQ is 132 kW-hr in a standard day and DG-QPQ has saved 107.5 kW-hr energy compared to DG-PQ due to the operation in Q mode. Fig.11(b) shows the load demand and energy requirement in every day of a month. As the demand is low during weekend, DG-QPQ generates only reactive power in the weekend and therefore no energy is required during the weekend. The total energy contributed by DG-QPQ in a month has been reduced to 3447.7kW-hr and the largest daily energy in a worst day of the month is 211.7kW-hr. DG-QPQ has saved an energy of 2346.6kW-hr in a month by operating in Q priority mode.

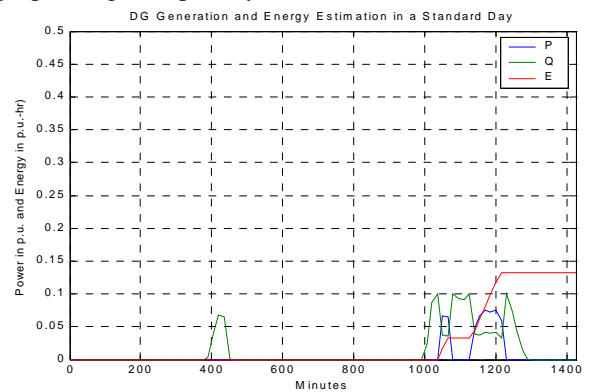


Fig.11(a): DG power generation and energy estimation for DG-QPQ (0.95 p.u. voltage threshold) in a standard day

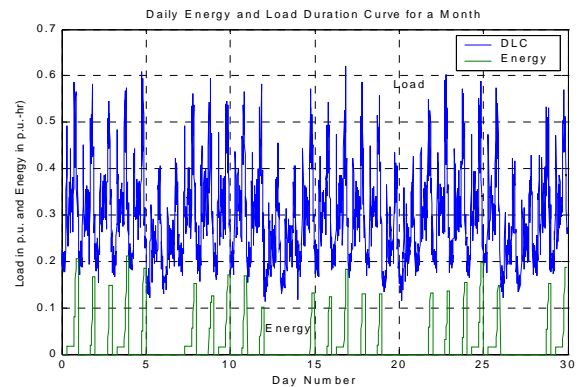


Fig.11(b): Daily load demand and DG energy for a month with DG-QPQ (0.95 p.u. voltage threshold)

#### 4.3 Comparative Study of DG-PQ and DG-QPQ

A comparative study has been performed with comparing the benefits obtained from DG-PQ and DG-QPQ. Energy requirements by the system for different voltage specifications have been assessed with the operation of DG-PQ and DG-QPQ at the threshold voltage of 0.945p.u., 0.96p.u., 0.97p.u., 0.98p.u. and 0.99p.u. separately. Table 2 presents the DG operating points in terms of load demands, and DG energy to meet the voltage requirements for a standard day. For higher threshold voltage, DG need to be operated at a lower value of load demand and the system requires more energy for this condition.

Load demand for every day in a month may be different at different times, which has been reflected in monthly load curve. The demand fluctuates due to the



customers' need in weekday and weekend and from season-to-season. Therefore, the DG needs to generate different amount of power at different time in response to customers' needs. DG energies for same voltage specification in different days may also be different. At the worst day of load demand, the lowest voltage in the system will be minimum for the month. For different voltage specifications in a month, DG response and energy estimation have been investigated and results are summarised in Table 3. The energy contributions by DG-PQ and DG-QPQ have been given in Table 3. The duration of no DG energy required is also computed. It is observed that DG-QPQ requires producing less energy than DG-PQ to meet same voltage specification. Fig.12 shows the comparison of monthly DG energy requirements and energy saving. It is found that DG operation modes play a big role in saving energy and fuel cost.

**Table 2: Energy estimation for a standard day**

Ref. Voltage	Mode of DG	Q injection started at load level	P injection started at load level	DG energy of the day	Energy saved by DG-QPQ
0.945 p.u.	DG-PQ	375.0 kVA	375.0 kVA	0.2071 p.u.-hr	0.0871 p.u.-hr
	DG-QPQ	375.0 kVA	468.7 kVA	0.1200 p.u.-hr	
0.95 p.u.	DG-PQ	368.7 kVA	368.7 kVA	0.2395 p.u.-hr	0.1075 p.u.-hr
	DG-QPQ	362.5 kVA	468.7 kVA	0.1320 p.u.-hr	
0.96 p.u.	DG-PQ	337.5 kVA	337.5 kVA	0.3180 p.u.-hr	0.1621 p.u.-hr
	DG-QPQ	337.5 kVA	468.7 kVA	0.1559 p.u.-hr	
0.97 p.u.	DG-PQ	237.5 kVA	237.5 kVA	0.4535 p.u.-hr	0.2837 p.u.-hr
	DG-QPQ	237.5 kVA	468.7 kVA	0.1698 p.u.-hr	
0.98 p.u.	DG-PQ	150.0 kVA	150.0 kVA	0.7836 p.u.-hr	0.6114 p.u.-hr
	DG-QPQ	150.0 kVA	468.7 kVA	0.1722 p.u.-hr	
0.99 p.u.	DG-PQ	125.0 kVA	125.0 kVA	1.4416 p.u.-hr	1.2694 p.u.-hr
	DG-QPQ	125.0 kVA	468.7 kVA	0.1722 p.u.-hr	

**Table 3: Results for a month**

Ref. voltage (p.u.)	Operating mode of DG	Largest daily energy (p.u.-hr) in the month	Total energy of the month (p.u.-hr)	Total energy (p.u.-hr) saved by DG-QPQ in a month	Total time (hours) of no DG energy in a month
0.945	DG-PQ	0.2709	5.0659	1.8289	286.25
	DG-QPQ	0.1996	3.2370		
0.950	DG-PQ	0.3015	5.7943	2.3466	274.25
	DG-QPQ	0.2117	3.4477		
0.960	DG-PQ	0.3777	5.6339	3.8429	243.50
	DG-QPQ	0.2321	3.7910		
0.970	DG-PQ	0.5329	11.2257	7.2284	90.00
	DG-QPQ	0.2403	3.9973		
0.980	DG-PQ	0.8548	20.7210	16.6771	4.00
	DG-QPQ	0.2427	4.0439		
0.990	DG-PQ	1.3537	35.5166	31.4727	0.00
	DG-QPQ	0.2427	4.0439		

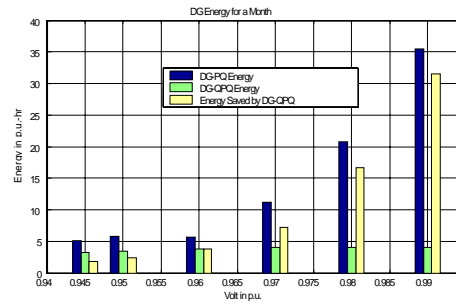


Fig.12: DG energy comparison for a month

## 7.0 Concluding Remarks

This study has highlighted the best achievement in network voltage specification using the minimum DG energy. The energy estimation is performed on an example SWER system and considered operating a single DG in various operation modes. From the simulation results it is found that system without DG is less capable of meeting voltage specifications. Without DG, the sample network exhibits poor voltage and cannot meet the voltage requirement during peak time of the day. DG real and reactive power injections are the keys for network voltage improvement. Pure real power generation requires heavy fuel injection to DG whereas reactive power generation does not depend on fuel. A comparative study between DG-PQ and DG-QPQ has been made from the benefits achieved by them and is reported here. From the simulation on the test system it is seen that no energy is required during weekend and less energy is required during weekdays if DG is operated in P-Q mode with Q priority. It is observed that DG operation with Q priority is most economical, as it requires generation of less energy and reduces the fuel requirement to meet same level of voltage specification.

## 8.0 Acknowledgment

The Authors gratefully acknowledge the support and cooperation of Ergon Energy personnel in providing data and advice on the operation of rural lines.

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