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POWER QUALITY STUDIES IN ISLANDING MODE OF OPERATION

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ABSTRACT
Deregulation, increasing demand, and barriers to building new generation and transmission infrastructure are all contributing to the increased interest in Distributed Generation. If the Distributed Generator (DG) is utilized to export power back to the utility distribution system, loss of the main supply can cause a severe overloading of the DG units. Consequently, the voltage and frequency will certainly fall below the statutory limits. Hence, it is imperative to control the voltage in the islanding mode of operation. Also, based on the operating conditions and several other criteria, islanding can cause both positive and negative impacts. It is necessary to effectively study the islanding operation in view of various aspects. Hence, this paper is concerned with the study of voltage control strategy, harmonic analysis and voltage sags for the operation of distributed generation systems (DGs) in the stand-alone mode of operation. Simulations have been carried on the IEEE 13-bus system using the PSCAD/EMTDC software in time domain using two different types of DGs in both the grid-connected and the stand-alone modes.

KEY WORDS
Distributed Generation, Grid-connected mode, Stand-alone mode, Voltage Control, Nonlinear load, Harmonics.

1. Introduction

The term "distributed generation (DG)" does not have a universal definition, but generally refers to smaller-scale generation located near the source of the load it serves [1]. Distributed generation strategically applies to relatively small generating units (typically less than 30 MW), at or near consumer sites, to meet specific customer needs, to support economic operation of the existing power distribution grid, or both [2]. DG is not a new concept, but dates back to the earliest days of the electric industry. It has been around for decades but what are new are size, technology, and location [3]. Some of the benefits using DGs are to help improve power quality and power supply flexibility, maintain system stability, provide the spinning reserve and reduce the transmission and distribution cost. DG can also be used to provide power supply to customers in the event of an outage or during scheduled interruptions [4]. Deregulation, increasing demand, and barriers to building new generation and transmission infrastructure are all contributing to the increased interest in DG [5].

There are various kinds of DG technologies. Many DG technologies have power conditioning subsystems that use power converters and pulse width modulation (PWM) techniques to permit grid connection of DG sources. The two modes of operation of DG focused in this paper are: stand-alone mode of operation and grid-connected mode of operation. The words stand-alone and islanding are used interchangeably. In the stand-alone mode, several DGs independently supply their loads with electrical power, like the parallel operation of the uninterruptible power supply (UPS) systems [6-7]. In the grid-connected mode of operation, the DGs are assumed to be disconnected to the utility. The introduction of distributed generators on the customer side in distribution systems has altered the traditional power flow and consequently the voltage profile in the network thereby making the voltage control more difficult. This implies that voltage profiles will fluctuate to a great extent, depending on production and consumption of energy in the network. Also, if the DG is utilized to export power back to the utility distribution system, loss of the main supply can cause a severe overloading of the DG units. Consequently, the voltage and frequency will certainly fall below the statutory limits. Hence, there is a need to control the voltage in the islanding mode of operation. Traditionally the voltage control in distribution network is performed in two ways:

- The control of the source voltage at the network substation by using tap changing transformers
- The control of the reactive power throughout the system, by using shunt capacitors/shunt reactors, auto transformers, synchronous condenser or static var compensator (SVC).

The type of loads in the distribution system can be broadly classified as linear and nonlinear loads. Nonlinear loads act as sources of harmonic currents and/or voltages. These loads that are frequently connected in the distribution systems are rectifiers, inverters, variable speed motor drives, arc furnaces, florescent lamps, etc. It is necessary to study how these power electronic interfaces for the distributed generators would affect the distribution system such as harmonic distortion. Also, there is a need to study about the interaction of the interfaces with the already existing sources of harmonic distortion and find out whether the net distortion is within the IEEE 519 [16] limits. Another issue of power quality addressed in this paper is voltage sags. Voltage sags are usually caused by the starting of a large induction motor or by short circuit faults in the utility system. Sags in the supply voltage can lead to unnecessary stoppage of operations. There is a need to study about these voltage sags too mainly due to the problems they cause on several types of sensitive equipment, such as adjustable speed drivers, process-control equipment, and computers.

The study in this paper investigates the performance of two types of distributed generators, synchronous and asynchronous generators. To study the effect of harmonics a nonlinear load, namely six-pulse converter which is extensively used in industrial loads is selected. To study the effect of faults, a single line to ground fault is simulated as a temporary fault. The available models in the PSCAD library have been used to develop the electrical circuits to simulate the steady-state operation of generators and the nonlinear load in the stand-alone mode of operation. The principle objective of the paper is to study the operation of these generators in the islanding mode and to study their effect on the voltage profile, harmonics and voltage sags of the system. Detailed load flows were carried out to ensure the voltage profiles in all the modes of operation are above the statutory limits. The approach and methodology of voltage control and harmonic analysis in the stand-alone mode of operation discussed in this paper is a new concept though the analysis is familiar.

2. Modeling of power system components

2.1 IEEE 13-bus System

To study the performance of the voltage profile in the islanding mode of operation, the IEEE 13-bus feeder [10] shown in Fig.1 is simulated using PSCAD/EMTDC software. The system under consideration is a three-phase unbalanced system. It consists of three-phase distribution lines, two-phase and one-phase lines with different loading in each phase, thereby making the whole system unbalanced.

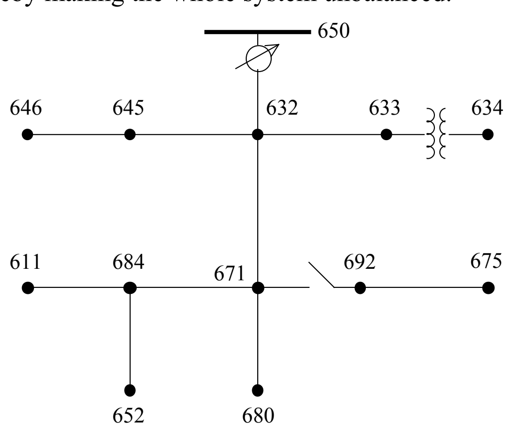

Fig.1. IEEE 13-bus system

Bus 650 is selected as the slack bus where the substation rated 5 MVA, 115 kV is connected to the system through 115/4.16 kV step-down transformer. The DG rated at 1.5 MVA, 0.48 kV is connected at bus 675 with a step-up transformer that connects the low voltage side of the DG to the high voltage side of the system.

2.2 Distributed Generator

The two different types of DGs that are used for the study are the synchronous generator and the induction generator. In PSCAD/EMTDC, the machine models (synchronous and asynchronous) are built based on general machine theory. The machine model makes use of the three-phase voltages calculated by EMTDC to update the injected currents, into EMTDC network. The SG and the AG models present in the PSCAD library have been used as examples of DGs. As the models used for this study are already developed, it is important to properly enter the machine's electrical parameters.

2.3 Synchronous Generator

The synchronous generator used for this study has a capacity of 1.5 MVA, 0.48 kV. The generator model consists of exciter, hydro governor and multimass. Synchronous generator includes an option to model two damper windings in the Q-axis and hence, it can be used as either a round rotor machine or a salient pole machine. The multimass is a shaft system which includes components like generator, exciter, governor and turbines. The outputs of these components from the multimass are used as inputs to the interfaced machine model [11]. The system voltage is maintained constant at Vref by varying the output field voltage using an IEEE SCRX type solid-state exciter. A mechanical torque signal provided at the governor input terminals helps in interfacing this governor model to the machine.

2.4 Induction Generator

The other DG technology that is used for this study is the induction generator which is also rated 1.5 MVA, 0.48 kV. The squirrel cage induction machine used as the asynchronous generator in this paper can be operated in either 'speed control' or 'torque control' mode. In speed control mode, the machine rotates at the speed specified at the input W. In torque control mode, the speed is calculated based on the machine inertia, damping, the input torque and the output torque [11]. Induction generators can fit very well in grid-connected energy recovery systems, where the prime mover speed is variable and the output frequency is constant. When an induction generator is operating in the stand-alone mode, the self excitation capacitors play a significant role in maintaining the magnitude and frequency of the output voltage [13].

2.5 Nonlinear load

A six-pulse converter present in the PSCAD library is used to study the effect of transients in the system in presence of the harmonics. The six-pulse converter is an AC-DC rectifier which uses thyristors as switching devices for converting AC to DC. The converter present in the PSCAD library is the Graetz bridge valve group which consists of an equivalent circuit of six thyristor valves. The numbering of the thyristor valves is also the firing order of the thyristors. Valve 2 is usually fired 60° after valve 1; valve 3 is fired 60° after valve 2, etc. The Graetz bridge calls the thyristor component routine six times per time step. It also includes built-in RC snubber circuits for each thyristor.

3. Results and Discussions

Simulation: All the simulations are carried out in the time domain for total time of 5s with plot step of 60μs. Initially, the simulations are carried out without any power factor correction capacitors. Load flow analysis is carried out and all the voltages of each phase at all the buses are recorded.

In the following figures, the lower case phasing refers to the voltages without capacitor and the upper case phasing refers to the voltages with capacitor. The voltage magnitudes in per unit are taken on the y-axis and the bus numbers are taken on the x-axis for each phase.

3.1 Grid-connected mode

In this mode DG is assumed to be disconnected. Fig.2 shows the results for this mode of operation. In order to bring all the voltages within ±6% range of the nominal 1pu value, power factor correction capacitors are placed at selected buses. These capacitors are placed at buses 671 and 645. Load flow analysis is performed again with the capacitors included in the system and the voltage magnitudes are recorded.

The following figure shows the results in the grid-connected mode with and without capacitors.

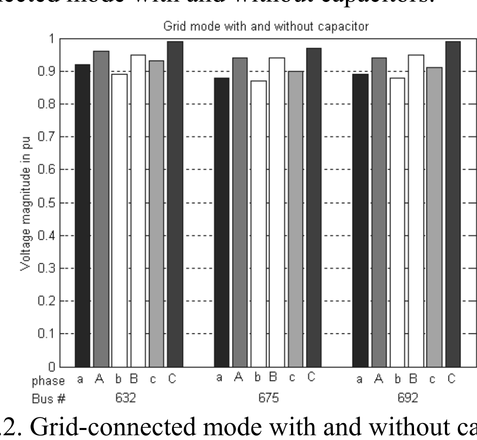

Fig.2. Grid-connected mode with and without capacitors

Fig.2 clearly shows the improved voltages with the insertion of capacitor in the system. The capacitor values are selected in such a way that the voltage magnitudes at all buses are above 0.94 pu.

3.2 Stand-alone mode

In the stand-alone mode of operation, the grid is disconnected from the system and the DG is connected at bus 675. The DG in this mode of operation supports only buses 675 and 692 with the rest of the system isolated with a switch. In this condition, the voltage profiles for the SG and IG are shown in figures 3 and 4 respectively.

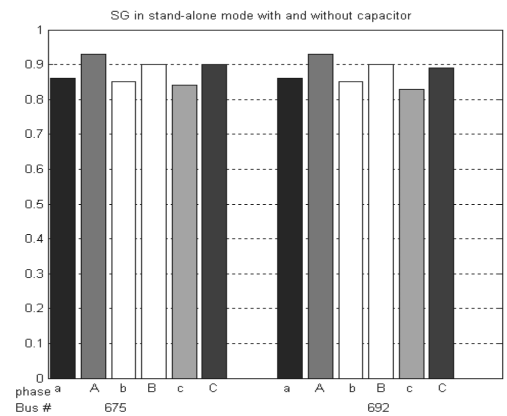

Fig.3. SG in stand-alone mode with and without capacitor

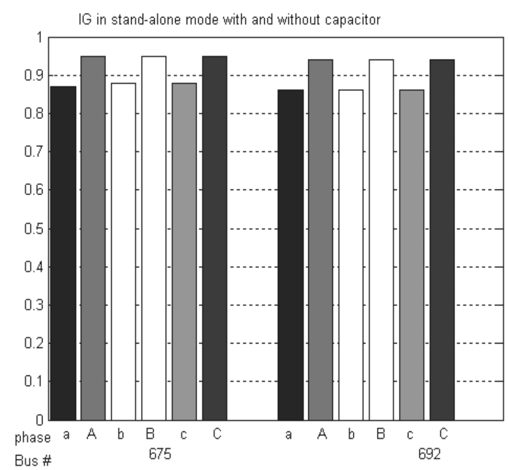

Fig.4. IG in stand-alone mode with and without capacitor

As seen from the results, the voltages have dropped significantly in the standalone mode of operation compared with the grid-connected mode. To improve these voltages, additional capacitor is connected at bus 692. The rating of the capacitor is chosen such that the voltage magnitudes at both the buses are above 0.94 pu. The improved voltages are noticed in the results.

3.3 Six-pulse rectifier

A nonlinear load i.e. a six-pulse rectifier is simulated with both DGs. The converter is connected at bus 692 with SG connected at bus 675, to study the effect of harmonics injected into the system. The drive is placed such a way that it consumes the same rating of the load that is present earlier at that bus. Simulations are carried out and the results for the total harmonic distortion (THD) for the currents and voltages (V675 and V692) in phase A, are noted which are as shown below.

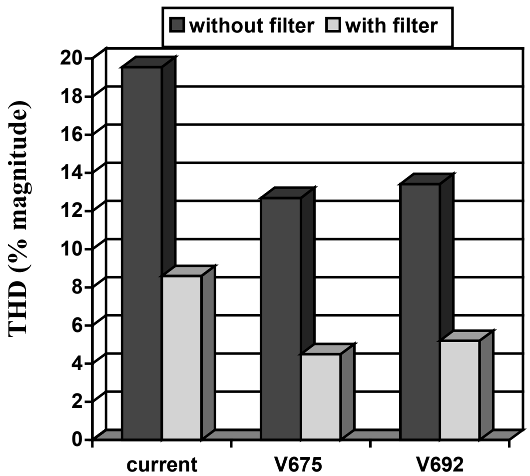

Fig.5. Six-pulse drive and SG rated 1.5 Mva

As seen from Fig.5, the distortions in the current and voltages strongly violate the IEEE 519 standards for Harmonic Control even in the presence of a filter. So, the generator is selected to have larger rating such as 10 MVA and the simulations are repeated. The reason for increasing the size of the generator is that a small DG does not have sufficient capacity to regulate the voltage and so the generators must be sized considerably larger than the load to achieve satisfactory power quality in isolated operation. The results for higher capacity SG are shown below.

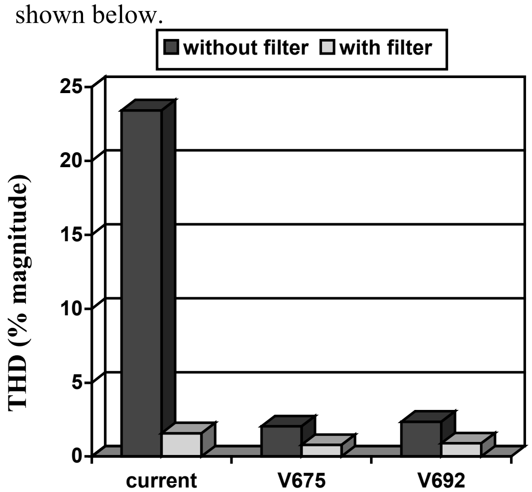

Fig.6. Six-pulse drive and SG rated 10 Mva

Comparing figures 5 and 6, it can be seen that in Fig.6 the distortions are within the limits after the filter is placed and thus justify the reason for a larger size of the generator.

The individual harmonic distortions in the current waveform in phase A, for SG rated 10 MVA are shown below. As expected, the 5th harmonic is the dominant harmonic due to the presence of a six-pulse drive. In order to minimize the harmonics, a filter tuned for 288Hz is placed at bus 692 and the simulations are repeated. The results of six-pulse drive for SG with and without filter are as shown below.

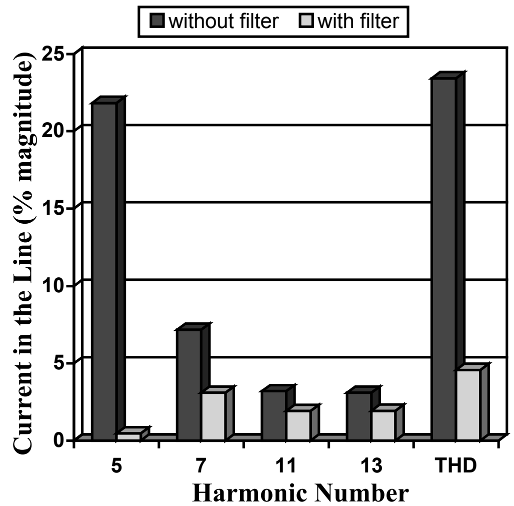

Fig.7. Individual Harmonic Distortion with SG

Now the simulations are repeated with Induction Generator as the Distributed Generator in presence of six-pulse drive. The results are shown in Fig.8. As seen from the results, the distortion values are high with the 5th harmonic as the dominant harmonic and are suppressed after the filter is placed thus lowering the THD value.

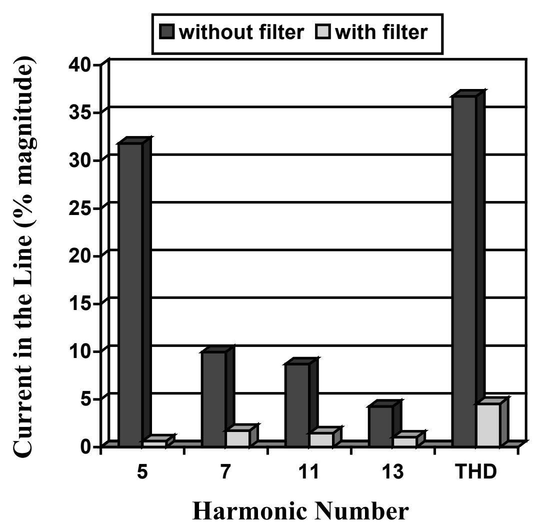

Fig.8. Individual Harmonic Distortion with IG

3.4 Voltage Sags

To study the effect of voltage sags in the islanding mode of operation, a temporary solid single line to ground (SLG) fault in phase A is simulated in both modes of operation. The fault is applied at bus 692 at 1.5 sec for duration of 0.05 sec. First, the fault is applied in the islanding mode without capacitor. Then the simulations are repeated with capacitor to study the effect of voltage sags in the presence of a capacitor. Load flow analysis for each case is carried out and the voltage magnitudes are noted down for each case. Also, each simulation is done for two-different load types every time to compare the results in view of load type. First the simulations are carried out with nonlinear load without capacitor in the islanding mode of operation. The results are presented for pre-fault (at 0.5 sec), during fault (at 1.53 sec) and post fault conditions (at 2 sec). The table below shows the voltage magnitudes at buses 675 and 692 in per-unit in all phases.

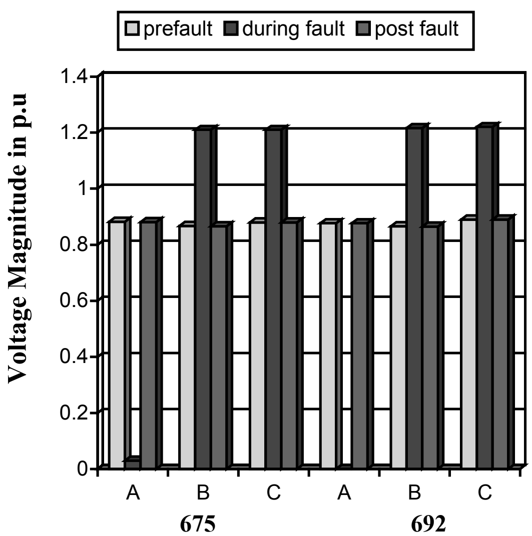

Fig.9. SLG fault voltage magnitudes with nonlinear load

As seen from Fig.9, the prefault and post fault voltages are almost identical. The voltages during fault are almost zero in the faulted phase and are very high in the other two phases.

The simulations are also carried with a higher rating of DG for comparison purposes. It was observed that the simulations with a bigger size DG are worst compared to a smaller size one. The reason for this is the inertia of the machine. The higher the size of the machine, the more the machine is disturbed when faults like this occur.

Now the results are presented in the following figure comparing two types of loads, P-Q load and a nonlinear load simulated in the previous section.

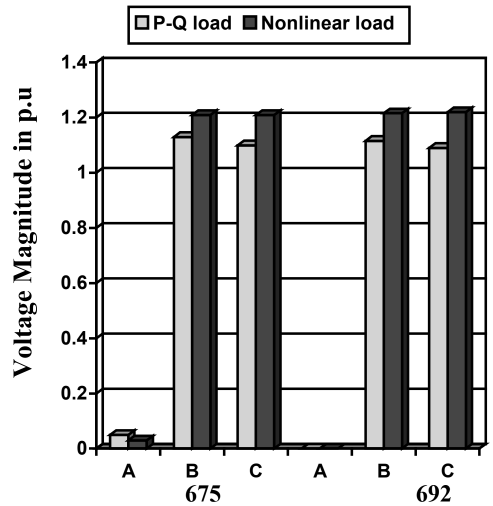

Fig.10. During fault voltages for different load types

From Fig.10, the voltage sags with P-Q load are less compared to the nonlinear load. This is due to the high unbalance nature of the nonlinear load. Now, the voltage magnitudes during fault for nonlinear load with and without capacitor are as shown below.

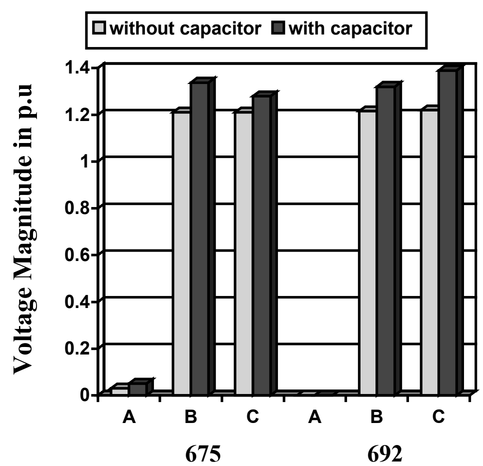

Fig.11. During fault voltages for nonlinear load with and without capacitor

The above figure shows that the voltage magnitudes without capacitor are less in presence of faults. The presence of capacitor worsens the situation due to its transient nature.

Also, when these simulations are repeated in the grid and DG mode, they were much better compared to the islanding mode of operation. The reason is the presence of the grid in that mode. Also, the voltage waveforms took more time to settle after the fault is recovered in the islanding mode of operation.

4. Conclusion

As seen from the results, the voltages in the stand-alone mode have dropped to a great extent compared with the grid-connected mode. When capacitors are connected at selected buses, the voltage magnitudes are improved by 3-6%, which is a considerable improvement. Also, the original power factor correction capacitors in the grid-connected mode need not necessarily improve the voltages in the stand-alone mode too. It is important to perform the load flow analysis when the DG is operating in the stand-alone mode and decide the location of the capacitors.

Analyzing the harmonics results, a higher rating of the synchronous generator is needed for satisfactory power quality in the islanding mode of operation. The individual and total harmonic distortions in the presence of non-linear load are very high and needs to be suppressed before they affect the power quality. Hence a shunt filter is tuned for 3% less than the 5^{th} harmonic frequency. The results in the presence of filter adhere to IEEE 519 standards.

Also, the results for voltage magnitudes during fault conditions presented some interesting conclusions in the islanding mode of operation. First, a case with P-Q load simulation is better than nonlinear load simulation with the same rating. The simulations without capacitor showed lesser voltage sag magnitudes compared to a case with capacitor. Finally, a higher rating of DG was disturbed to a great extent during fault conditions though it minimized the harmonic distortions.

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