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Distributed Generation and its Impact on Power System

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The penetration of distributed generation (DG) into the main electricity network is changing the paradigm we used to live with. DG is gaining interest worldwide as numerous benefits are associated with this change due to penetration of DG. In this paper the main purpose is to show the basics of distributed generation. The different ways to interface the DG with the utility system are also reported. Penetration of a DG into an existing distribution system has many impacts on the system and equipment operations in terms of steady-state operation, dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers. However here in this paper the more focus in on impact of DG on power quality pointing out its positive and negative impacts and its solutions. At last to support this arguments analysis of results are shown which are directly taken from the references, where the results revels the effect of DG on power quality and based on that some conclusions are documented.

Keywords: *Distributed generation (DG), Power quality and Distributed power generation system (DPGS).*

1.0 INTRODUCTION

In recent years, fossil fuel is the main energy supplier of the worldwide economy, but the recognition of it as being a major cause of environmental problems makes the mankind to look for alternative resources in power generation. The demand of power is escalating in the world of electricity. This growth of demand triggers a need of more power generation. DG uses smaller-sized generators than does the typical central station plant. Hence government tries to replace conventional power generation system with the distributed generation (DG) systems. Distributed generators are small scale generators located close to consumers; normally Distributed Generators are of 1 kW–100 MW.

In Traditional Concept of Power System as shown in Figure 1, in the first stage the electricity is generated in large generation plants, located in non-populated areas away from loads to get round with the economics of size and environmental issues. Second stage is accomplished with the support of various equipments such as transformers, overhead transmission lines and underground cables. The last stage is the distribution, the link between the utility system and the end customers. This stage is the most important part of the power

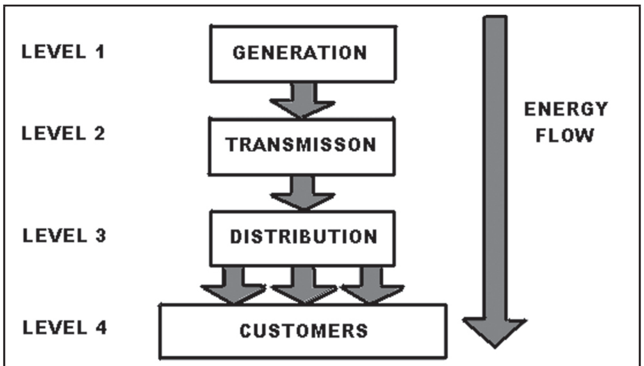

FIG.1 TRADITIONAL INDUSTRIAL CONCEPTION OF THE ELECTRICAL ENERGY SUPPLY [1].

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system, as the final power quality depends on its reliability [1].

The electricity demand is increasing continuously. Consequently, electricity generation must increase in order to meet the demand requirements. Traditional power systems face this growth; installing new support systems in level 1. Whilst, addition in the transmission and distribution levels are less frequent.

Nowadays, the technological evolution, environmental policies, and also the expansion of the finance and electrical markets, are promoting new conditions in the sector of the electricity generation [1].

In the New Concept of Power System as shown in Figure 2, new technologies allow the electricity to be generated in small sized plants. Moreover, the increasing use of renewable sources in order to reduce the environmental impact of power generation leads to the development and application of new electrical energy supply schemes.

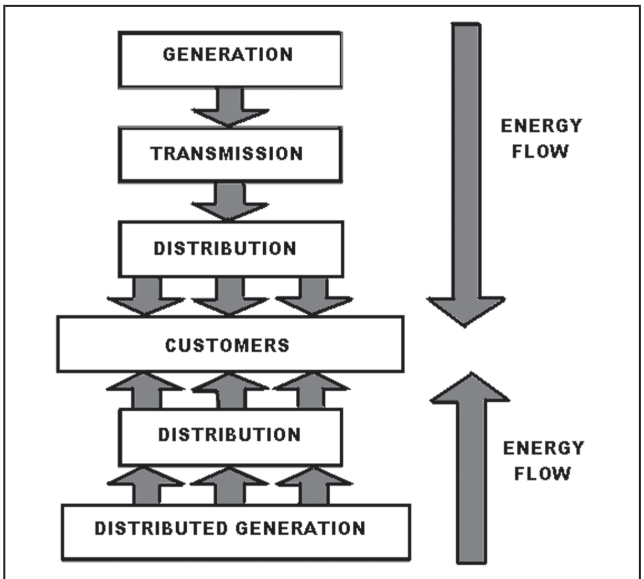


FIG. 2 NEW INDUSTRIAL CONCEPTION OF THE ELECTRICAL ENERGY SUPPLY [1].

2.0 DPGS (DISTRIBUTED POWER GENERATION SYSTEM) STRUCTURE

A general structure for distributed systems is illustrated in Figure 3. The input power is transformed into electricity by means of a power conversion unit whose configuration is closely related to the input power nature. The electricity produced can be delivered to the local loads or to the utility network, depending where the generation system is connected. One important part of the distributed system is its control. The control tasks can be divided into two major parts. One is Input-side controller which can have the following tasks: Main property to extract the maximum power from the input source; Control input power; To maintain the generator voltage level; Speed control of the generator as if the speed is not maintained the generator will be getting shutdown; Naturally, protection of the input-side converter is also considered in this controller. Another is Grid-side controller which can have the following tasks: Control of active power generated to the grid; Control of reactive power transfer between the DPGS and the grid; Control of dc-link voltage; Ensure high quality of the injected power; Grid synchronization.

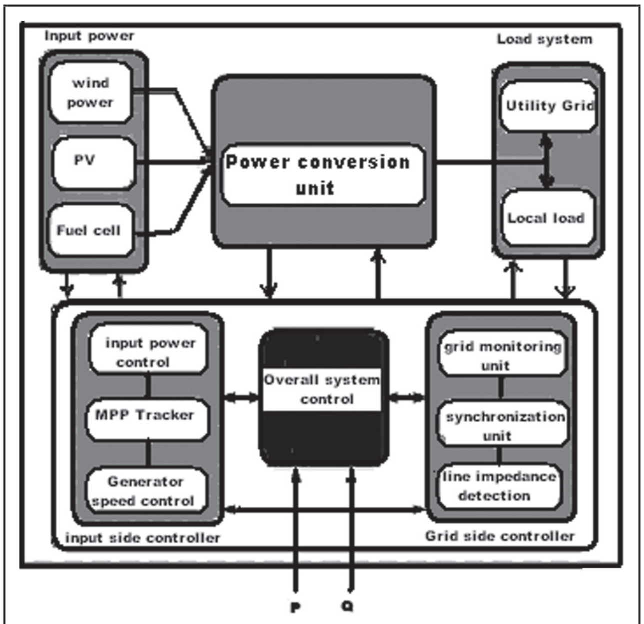


FIG. 3 GENERAL STRUCTURE FOR DISTRIBUTED POWER SYSTEM HAVING DIFFERENT INPUT POWERS [2].

The items listed above for the grid-side converter are the basic features this converter should have. Additionally, ancillary services like local voltage and frequency regulation, voltage harmonic compensation, or active filtering might be requested by the grid operator [2].

3.0 TYPES AND TECHNOLOGIES OF DG

There are different types of DGs from the constructional and technological points of view as shown in Figure 4. These types of DGs must be compared to each other to help in taking the decision with regard to which kind is more suitable to be chosen in different situations. There are various types of distributed generation technologies ranging from the well established reciprocating engines and gas turbines to more recent types of renewable sources such as wind farms and photovoltaic. Emerging technologies such as fuel cells and micro turbines are recently commercialized. DG technologies can generally fall under two main categories [3].

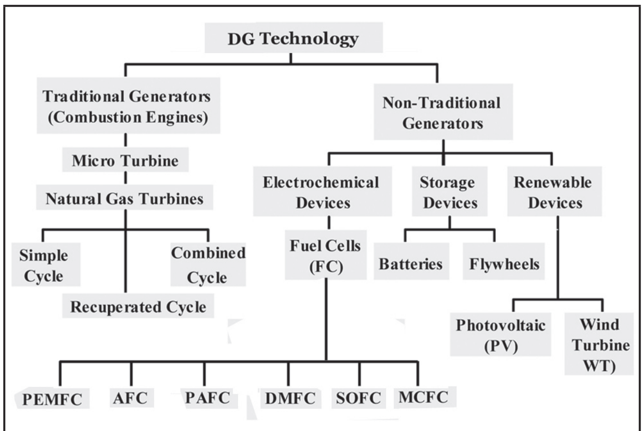


FIG.4 DISTRIBUTED GENERATION TYPES AND TECHNOLOGIES [3].

DG includes both Traditional generators and Non-Traditional generators. Traditional generators such as gas turbine, micro turbine etc. and Non-Traditional generators includes electromechanical devices such as fuel cells (FC); storage devices such as batteries, flywheels etc. and renewable device such as PV and wind turbine.

4.0 CONTROL STRUCTURE FOR GRID-CONNECTED DPGS

Synchronous reference frame control, also called dq control, uses a reference frame transformation module, e.g., abc→dq, to transform the grid current and voltage waveforms into a reference frame that rotates synchronously with the grid voltage. By means of this, the control variables become dc values; thus, filtering and controlling can be easier achieved.

A schematic of the dq control is represented in Figure 5. In this structure, the dc-link voltage is controlled in accordance to the necessary output power. Its output is the reference for the active current controller, whereas the reference for the reactive current is usually set to zero, if the reactive power control is not allowed. In the case that the reactive power has to be controlled, a reactive power reference must be imposed to the system. The dq control structure is normally associated with proportional–integral (PI) controllers since they have a satisfactory behavior when regulating dc variables.

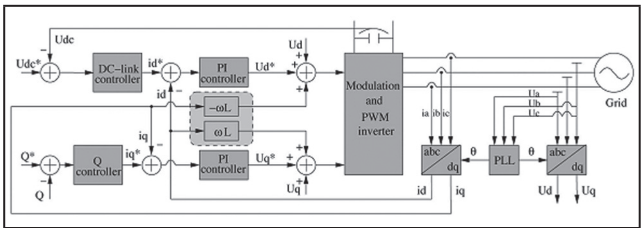


FIG. 5 GENERAL STRUCTURE FOR SYNCHRONOUS ROTATING FRAME CONTROL STRUCTURE [2].

The matrix transfer function of the controller in dq coordinates can be written as

$$G_{PI}^{(dq)}(s) = \begin{bmatrix} kp + \dfrac{ki}{s} & 0 \\ 0 & kp + \dfrac{ki}{s} \end{bmatrix} \quad \text{.... (1)}$$

Where, Kp is the proportional gain and Ki is the integral gain of the controller. Since the controlled current has to be in phase with the grid voltage, the phase angle used by the abc→dq transformation module has to be extracted from the grid voltages. As a solution, filtering of the grid voltages and using arctangent function to extract the phase angle can be a possibility. In addition, the phase-locked loop (PLL) technique became a state of the art in extracting the phase angle of the grid voltages in the case of distributed generation systems. PLL is used to synchronize the DG system with grid. For improving the performance of PI controller in such a structure as depicted in Figure 5, cross-coupling terms and voltage feed forward are usually used. In any case, with all these improvements, the compensation capability of the low-order harmonics in the case of PI controllers is very poor, standing as a major drawback when using it in grid connected systems. Also the tuning of PI is a big problem [2].

5.0 IMPACT OF DG ON POWER QUALITY

The DG penetration in the grid poses new challenges and problems to the network operators as these can have a significant impact on the system and equipment operations in terms of steady-state operation, dynamic operation, reliability, power quality, stability and safety for both customers and electricity suppliers. However here in this report the more focus is on impact of DG on power quality.

The impact of the DG on power quality depends on many factors including:

- Type of DG.
- Its interface with the utility system.
- The size of the DG unit, its intended mode of operation and expected output fluctuation.
- The total capacity of the DG relative to the system.
- Size of generation relative to the load at the interconnection point.
- Feeder voltage regulation practice.

DG has both positive and negative impact on power Quality. In general, back-up generation and on-site power supply provided by DG improve the system power quality in terms of sustained interruption and voltage sags. However, some issues might arise when distributed generators, with their different types and technologies, are interconnected to the utility distribution system. Among these issues are voltage regulation, harmonics, voltage flicker, islanding etc. [4].

5.1 Sustained interruption

Much of the DG installed as backup generation. The most common technology used for backup generation is diesel-gensets. The bulk of the capacity of this form of DG can be realized simply by transferring the load to the backup system. However, there will be additional power that can be extracted by paralleling with the power system. Many DG installations will operate with better power quality while paralleled with the utility system because of its large capacity.

Not all DG technologies are capable of significant improvements in reliability. To achieve improvement, the DG must be capable of serving the load when the utility system cannot [5]. For example, a home owner may install a rooftop photo-voltaic solar system with the expectation of being able to ride through rotating blackouts. Unfortunately, the less costly systems do not have the proper inverter and storage capacity to operate stand-alone. Therefore, there is no improvement in reliability.

Utilities may achieve improved reliability by employing DG to cover contingencies when part of the delivery system is out of service. In this case, the DG does not serve the entire load, but only enough to cover for the capacity that is out of service. This can allow deferral of major construction expenses for a few years. The downside is that reliance on this scheme for too many years can ultimately lead to worse reliability. The load growth will overtake the base capacity of the system, requiring load shedding during peak load conditions or resulting in the inability to operate the system at acceptable voltage after a fault [5].

5.2 Voltage Regulation

Over-voltages due to reverse power flow: If the downstream DG output exceeds the downstream feeder load, there is an increase in feeder voltage with increasing distance. If the substation end voltage is held to near the maximum allowable value, voltages downstream on the feeder can exceed the acceptable range [5].

Large voltage changes are also possible if there were a significant penetration of dispersed, smaller DG producing a constant power factor. Suddenly connecting or disconnecting such generation can result in a relatively large voltage change that will persist until recognized by the utility voltage-regulating system. This could be a few minutes, so the change should be no more than about 5%. One condition that might give rise to this would be fault clearing on the utility system. All the generation would disconnect when the fault occurs, wait 5 min and then reconnect. Customers would first see low voltage for a minute, or so, followed 5 min later by high voltages [5].

Figure 6 illustrates one voltage regulation problem that can arise when the total DG capacity on a feeder becomes significant. This problem is a consequence of the requirement to disconnect all DG when a fault occurs. Figure 6(a) shows the voltage profile along the feeder prior to the fault occurring. The intent of the voltage regulation scheme is to keep the voltage magnitude between the two limits shown. In this case, the DG helps to keep the voltage above the minimum limit and, in fact, is large enough to give a slight voltage rise toward the end of the feeder.

When the fault occurs, the DG disconnects and may remain disconnected for up to 5 min. The breaker recloses within a few seconds, resulting in the condition shown in Figure 6(b). The load is now too great for the feeder and the present settings of the voltage regulation devices. Therefore, the voltage at the end of the feeder sags below the minimum limit and will remain low until voltage regulation equipment can react. This can be the better part of a minute or longer, which increases the risk of damage to load equipment due to excessively low voltages.

Solutions include:

- Requiring customer load to disconnect with the DG. This may not be practical for widespread residential and small commercial loads. Also, it is difficult to make this transition seamlessly and the load may suffer downtime anyway, negating positive reliability benefits of DG.
- Installing more voltage regulators, each with the ability to bypass the normal time delay of 30–45 s and begin changing taps immediately. This will minimize the inconvenience to other customers.
- Allow DG to reconnect more quickly than the standard 5 min disconnects time. This would be done more safely by using direct communications between the DG and utility system control.
- Limit the amount of DG on the feeder.

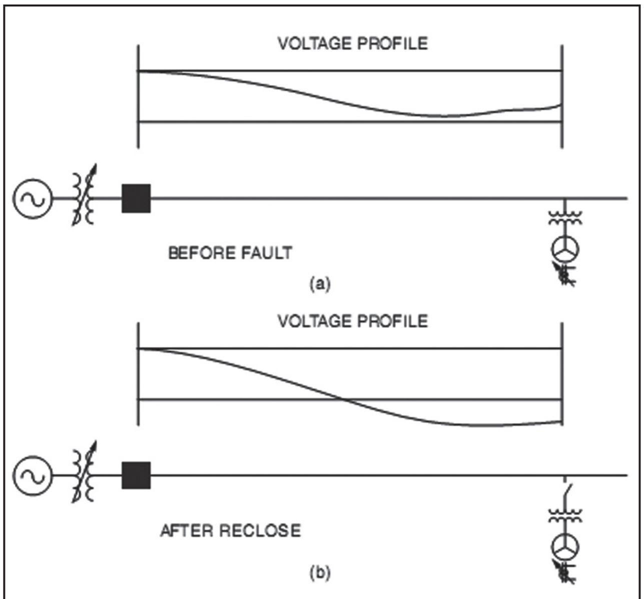


FIG. 6 VOLTAGE PROFILE CHANGE WHEN DG IS FORCED OFF TO CLEAR THE FAULTS [5].

5.3 Harmonic Distortion

Voltage harmonics are virtually always present on the utility grid. Nonlinear loads, power electronic loads, and rectifiers and inverters in motor drives are some sources that produce harmonics. The effects of the harmonics include overheating and equipment failure, faulty operation of protective devices, nuisance tripping of a sensitive load and interference with communication circuits. All power electronic equipments create current distortion that can impact neighboring equipment. DG like PV, fuel cells are likely to introduce harmonics problem in the system. Harmonics from DG come from inverters and some synchronous machines. The PWM (pulse width modulation) switching inverters produce a much lower harmonic current content than earlier line-commutated, thyristor-based inverters [6].

One new distortion problem that arises with the modern inverters is that the switching frequencies will occasionally excite resonances in the primary distribution system. This creates non-harmonic frequency signals typically at the 35th harmonic and higher riding on the voltage waveform. This has an impact on clocks and other circuitry that depend on a clean voltage zero crossing. A quick fix is to add more capacitance in the form of power factor correction capacitors, being careful not to cause additional harmful resonances [7].

Solutions include:

- Newer PWM inverters have lower current distortion.
- Use non-resonant switching frequencies.
- Use power factor correction capacitors.

5.4 Flicker

Flicker is a low-frequency phenomenon in which the magnitude of the voltage and frequency changes at such a rate as to be perceptible to human eye. Some energy source (e.g., wind turbine or fuel cell) has some mechanical (or chemical) fluctuations in power output and some electrical equipment (e.g., the dc bus and inverter) does not have sufficient energy storage to smooth out these fluctuations. This will result in fluctuations in the power delivered by a DG and can cause flicker in the power system in a fashion very similar to that caused by load fluctuations [8].

Solutions include:

- Utility companies try to limit flicker so that it is at a level that cannot be perceived by the human eye. This is accomplished by designing the power system to be sufficiently robust so that smaller load variations do not create noticeable voltage variations.
- It is also controlled by imposing limits on the types of loads that are allowed to connect at various points on the system.
- When a larger DR unit is applied on a feeder, rapid response voltage regulators (static Var compensators) or fast-response reactive compensation using inverter reactive-power capabilities can do mitigation of flicker.
- Energy storage technologies can be applied to smooth the output fluctuations of solar and wind energy systems.

5.5 Voltage Sags

Voltage Sag is the event that can last from half of a cycle to several seconds. The ability of a DG to counteract voltage sags depends on its type and location. Generally DG has positive impact on voltage sags. Also utility faults are responsible for voltage sag [9].

Solutions include:

- Large DG with synchronous generators can help to support the voltage and reduce voltage sags on local facility.
- However, impedance of interconnection transformers might prevent any impact on adjacent loads on the feeder.
- Inverter-based distributed generators can be controlled to supply reactive power for voltage support during sag.

5.6 Islanding

One of the technical issues created by DG interconnection is inadvertent islanding. Islanding occurs when a portion of the distributed system becomes electrically isolated from the remainder of the power system, yet continues to be energized by DG connected to the isolated subsystem. It can be desirable to permit such islanded operation to increase customer reliability, and this is often done where the DG provides backup power to the facility where it is installed. However, considerable engineering effort, control functionality, and communications infrastructure are necessary to make intentional islanding viable where the island includes a portion of primary system and other loads. Even greater requirements are necessary to coordinate the operation of more than one DG in an island [10].

When the DG capacity is small compared to the system, the impact will normally be insignificant. With higher values of penetration, compared to local load and system capacity, measures intended to limit unintentional islanding can aggravate local disturbances. If DG penetration becomes widespread, the anti islanding measures may also impact bulk power system voltage and frequency stability.

5.6.1 Formulation of Islands

A typical power distribution system in North America is shown in Figure 7. The substation steps down transmission voltage into distribution voltage and is the sending end of several distribution feeders. One of the feeders is shown in detail. There are many customer connection points in the feeder. Large distributed generators are typically connected to the primary feeders (DG1 and DG2). These are typically synchronous and induction generators at present. Small distributed generators such as inverter based PV systems are connected to the low voltage secondary feeders (DG3).

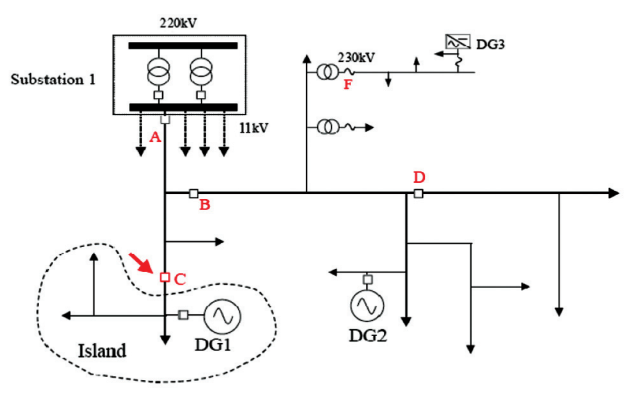


FIG. 7 TYPICAL DISTRIBUTED SYSTEM WITH DG's [10].

An island situation occurs, for example, when recloser C opens. DG1 will feed into the resultant island in this case. The most common cause for a recloser to open is a fault in the downstream of the recloser. A recloser is designed to open and re-close two to three times within a few seconds. The intention is to re-connect the downstream system automatically if the fault clears by itself. In this way, temporary faults will not result in the loss of downstream customers. An island situation could also happen when the fuse at point F melts. In this case, the inverter based DG will feed the local loads, forming a small islanded power system.

5.6.2 Implications of unintentional islanding

The island is an unregulated power system. Its behavior is unpredictable due to the power mismatch between the load and generation and the lack of voltage and frequency control. The main concerns associated with such islanded systems are:

- The voltage and frequency provided to the customers in the islanded system can vary significantly if the distributed generators do not provide regulation of voltage and frequency and do not have protective relaying to limit voltage and frequency excursions, since the supply utility is no longer controlling the voltage and frequency, creating the possibility of damage to customer equipment in a situation over which the utility has no control. Utility and DG owners could be found liable for the consequences.
- The distributed generators in the island could be damaged when the island is reconnected to the supply system. This is because the generators are likely not in synchronism with the system at the instant of reconnection. Such out-of-phase reclosing can inject a large current to the generators.
- Protection systems on the island are likely to be uncoordinated, due to the drastic change in short circuit current availability.

5.6.3 Out-of-phase Reclosing

Out-of-phase reclosing creates large mechanical torques and currents which can damage the generator or the prime mover if rotating generators are used. Out-of-phase reclosing can also produce transients which are potentially damaging to utility and other customer equipment. Significant shunt capacitance will usually be present in the islanded system in order to provide the reactive power balance required for the island to persist. Out-of-phase reclosing, if it occurs at a voltage peak, will generate a very severe capacitive switching transient. In a lightly damped system, the crest over-voltage can approach three times rated voltage. With more typical damping, the switching transient can exceed 2 p.u. and utility surge arresters and customer equipment are susceptible to damage. Figure 8 provides analyzed results for an out-of-phase reclosing, showing the high transient voltage which can result [11].

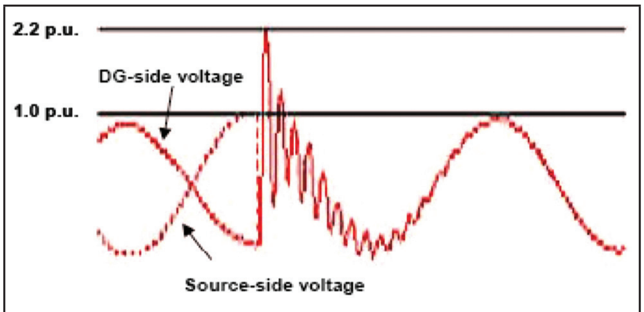


FIG. 8 PHASE VOLTAGES ON SOURCE AND DG SIDE FOR A SIMULATION OF 180º OUT-OF-PHASE RECLOSING [11].

Out-of-phase reclosing can also cause unusually-high inrush currents in transformers and motors. The simultaneous inrush to many devices downstream of an over current protective device can cause nuisance operation of fuses and circuit breakers on both the utility system and within customer facilities. Large transient torques can also occur on motor loads, possibly leading to mechanical damage. The following analyzed results shown in Figure 9 show the 3-phase voltage and current signals under Islanding condition retrieved at the target DG location (starts at 0.3 sec) [12].

6.0 ANALYSIS OF RESULTS

The previous sections discussed the impact of DG on the distribution network to which it is interconnected, pointing out its main supporting benefits as well as the operating conflicts that might arise with more focusing on power quality issues. To support this argument, analysis of results is provided in this chapter, which is taken from reference [4], to reveal the effect of DG on

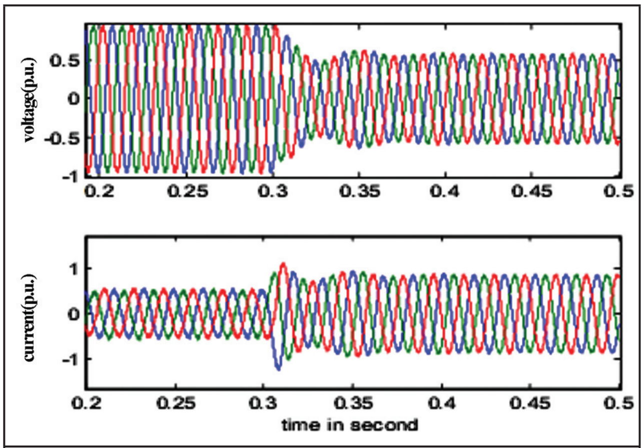


FIG. 9 THREE-PHASE VOLTAGE AND CURRENT SIGNALS UNDER ISLANDING CONDITION RETRIEVED AT THE TARGET DG LOCATION (STARTS AT 0.3 SEC) [12].

power quality. Figure 10 shows the IEEE 34-bus distribution system, with DG and local load connected at the end of the feeder. This system was simulated on EMTDC/PSCAD software [4]. The purpose of the analysis is to study the effect of a 1 MW synchronous generator based DG and a 100 kW inverter-based DG on voltage regulation, voltage sag and harmonics.

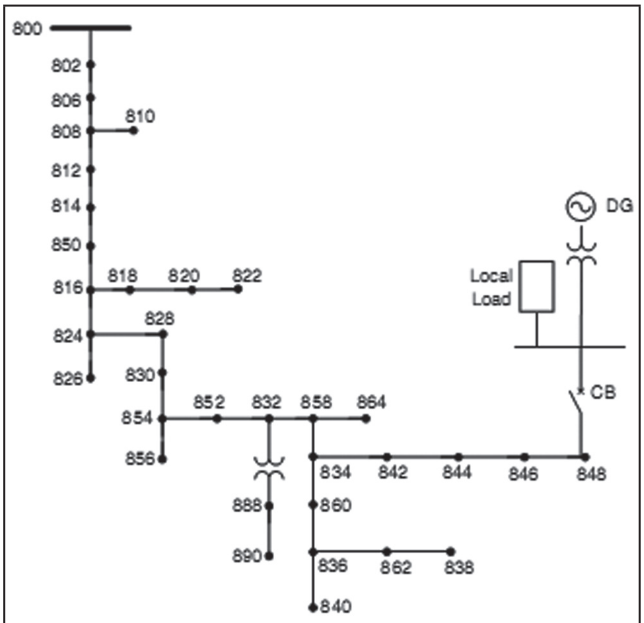
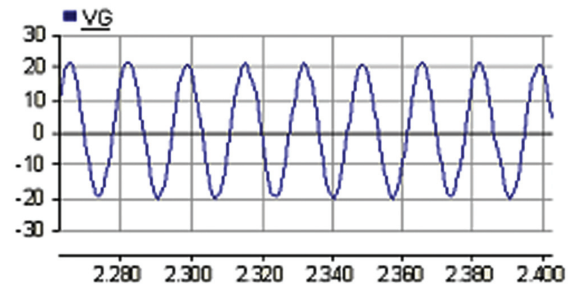


FIG. 10 IEEE 34-BUS DISTRIBUTION SYSTEM WITH DG [4].

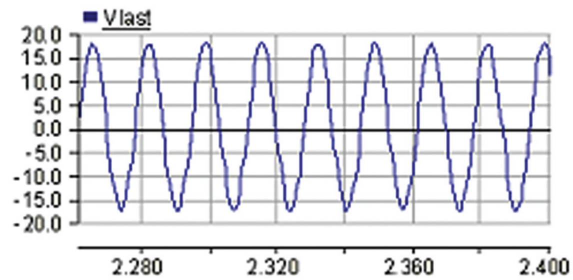
6.1 One MW Synchronous generator based DG.

A 1 MW synchronous generator based DG is interconnected at the end of the 34-bus radial distribution system; i.e. at node 848. The utility supply is at the beginning of the main feeder; at node 800. The effect of DG on voltage regulation is studied by measuring the voltage near the supply (node 802) and that at the end of the main feeder (node 846), with and without the DG. The voltage at node 802 near the utility supply is denoted VG while that at node 846 is denoted V_{last}.

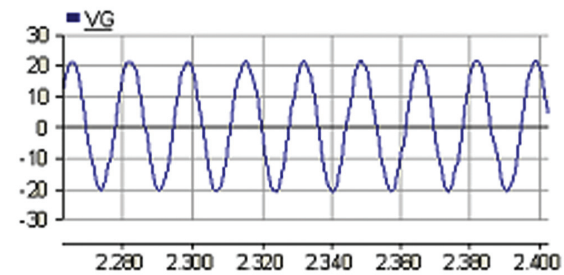
The analyzed waveforms are as show in Figures 11(a–j), which are simulation results of 1 MW Synchronous generator based DG [4].



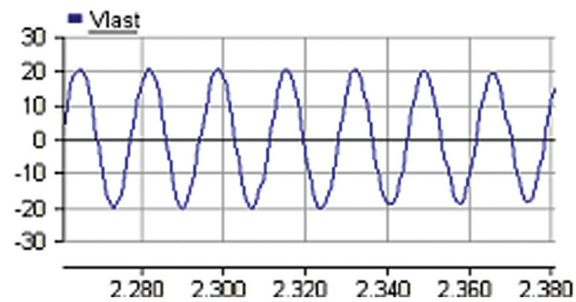
(a) The voltage near utility supply without DG



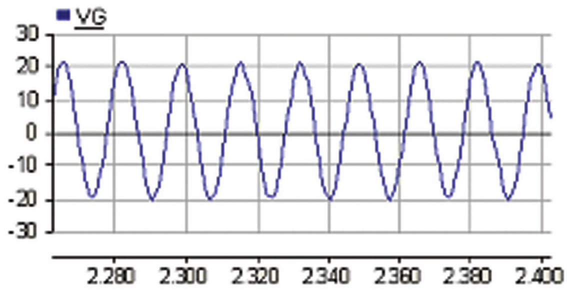
(b) The voltage at the end of feeder without DG



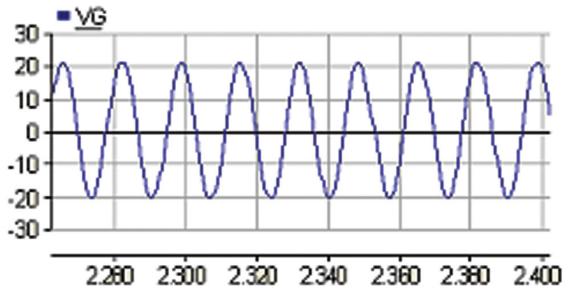
(c) The voltage near utility supply with DG



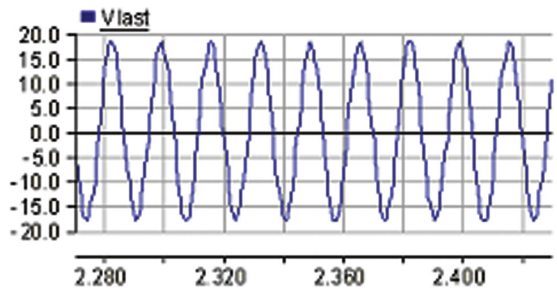
(d) The voltage at the end of feeder with DG



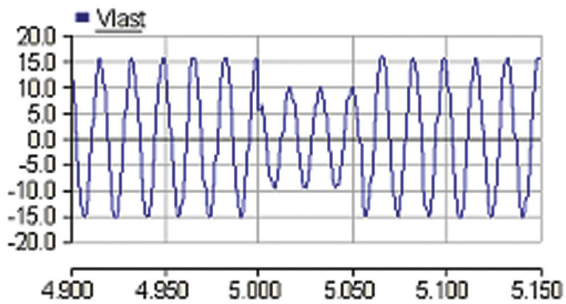
(e) The voltage near utility supply with excess load and without DG



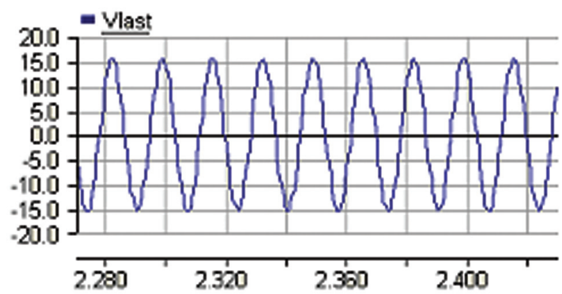
(f) The voltage at the end of the feeder with excess load and without DG



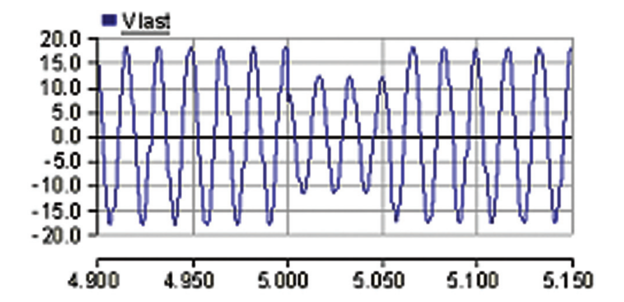
(g) The voltage near utility supply with excess load and with DG



(h) The voltage at the end of the feeder with excess load and with DG



(i) Voltage sag without DG



(j) Voltage sag with DG

FIG. 11 SIMULATION RESULTS OF 1 MW SYNCHRONOUS GENERATOR BASED DG.

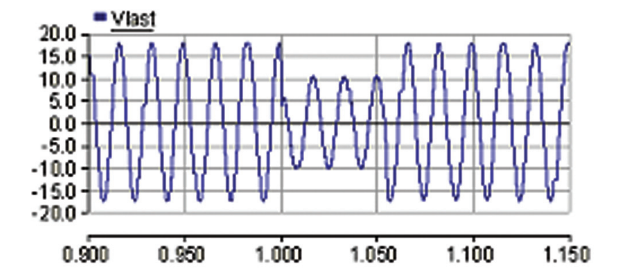
The first analysis is done without the DG or the local load. The waveforms for VG and V_{last} are shown in Figures 11(a–b). The results are: VG = 21 kV; V_{last} = 17.5 kV; VR = 16.7%. When the DG is connected, the voltage at the end of the feeder is boosted, whereas the voltage near the utility supply remains the same. This is revealed in Figures 11(c–d). The results are: VG = 21 kV; V_{last} = 19.5 kV; VR = 7%. The results significantly show the effect of DG on voltage regulation and the improvements that can be achieved. It is now even possible to add another load at the end of the feeder. This is one of the main supporting benefits of DG that it improves the voltage profile across the distribution feeder and allows for load growth without the need for new transmission lines.

A local load now is added as shown in Figure 11. The voltages are first measured without DG to see how far the excess load will worsen the voltage regulation. The voltages waveforms are given in Figures 11(e–f). The results are: VG = 20.5 kV; V_{last} = 15.5 kV; VR = 24.4%. The DG is now connected at the end of the feeder and the new voltages are measured to show the capability of the system to properly supply this excess load after connecting the DG. Figures 11(g–h) reveal the effect of the DG and the improvements that could be achieved concerning the voltage profile across the feeder even after adding this excess local load. The results are: VG = 21 kV; V_{last} = 18 kV; VR = 14.3%.

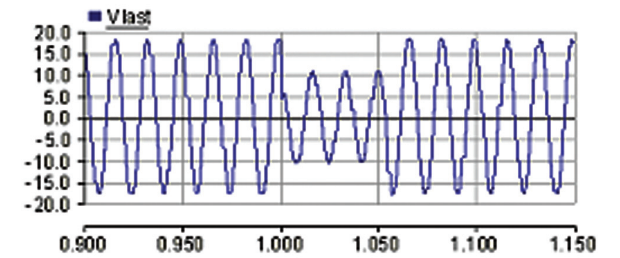
The effect of the synchronous based DG on voltage sag is now studied by applying a fault at t = 5 seconds for a duration of 0.05 seconds and investigating the voltage at the end of the feeder (near the DG) in both cases; with and without the DG. The waveforms of the voltages for both cases are shown in Figures 11(i–j). Without the DG, the voltage sag is 62%, whereas when the DG is connected an improvement takes place with voltage sag equals to 67%.

6.2 100 kW Inverter-Based DG

The effect of inverter-based DG on the harmonics in the system is studied in this section by introducing some non- linear loads to the distribution system, then calculating the total harmonic distortion (THD) for both the voltage and the current in both cases; with and without the DG. The analyzed waveforms are as show in Figures 12(a–b), which are simulation results of 100 kW Inverter-Based DG [4].



(a) Voltage sag without the inverter-based DG.



(b) Voltage sag with the inverter-based DG.

FIG. 12 SIMULATION RESULTS OF 100 kW INVERTER-BASED DG.

Without the DG, the voltage THD is 4.3% while the current THD is found to be 12.8%. When the inverter-based DG is interconnected to the network, the voltage THD remained the same while the current THD increased to 14.5%. This completely supports the fact that inverter-based DG introduces or increases the harmonics in the system to which it is connected. It is worth mentioning here that the severity of the introduced harmonics depends on the technology of the power electronic inverter.

The effect of the inverter-based DG on voltage sag is studied by applying a fault at t = 1 sec for a duration of 0.05 sec and examining the voltage at the end of the feeder (near the DG) in both cases; with and without the DG.

The results shown in Figures 12(a–b) clearly support the fact that the inverter-based DG doesn't affect the voltage regulation or sag, unless it is controlled to provide reactive power. The voltage sag is the same is both cases; with and without the inverter-based DG and it is equal to 59%.

7.0 CONCLUSION

Distributed Generation is expected to play a greater role in power generation over the coming decades, especially close to the end-use low voltage consumer side. While DG may greatly improve reliability for some DG owners, it can reduce it for other customers on the feeder as some problems concerning power quality and system reliability may arise under certain circumstances. Also it can be concluded that when interconnecting DG to the power system, the issues must be considered which could affect power quality and safety.

Penetration of DG has both positive and negative impact on power quality. Large synchronous generator based DG can improve the voltage regulation and voltage sags. Whereas the small inverter based DG increase current harmonic distortion into the system. It doesn't affect the voltage regulation and voltage sags.

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