Impact of Distributed Generation on the Stability of Electrical Power Systems

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Abstract— **This paper aims at analysing the potential impacts that distributed generation might have on the stability of electrical power networks. In particular, the performance of a power system with significant penetration of distributed resources is described to assess different types of stability of the bulk network. For this purpose, a hypothetical network is simulated, assuming a large number of fuel cells and micro-turbines as dispersed units in the low-voltage area. The investigation is carried out at constant load demands but with different contributions from fuel cells and micro-turbines. Thus, the rated and supplied powers of the conventional synchronous generators are adjusted to achieve the power balance in the network. With each penetration level of the distributed generation, the performance of the network is studied and different stability classes are analysed. The results are compared with the performance of the network without any distributed generation, as a reference case, to highlight the influence of penetration levels of such units on the stability of the entire network.**

Index Term— Distributed generation, frequency stability, oscillatory stability, transient stability, voltage stability

I. INTRODUCTION

THE concept of integrating small and medium size generating units into distribution networks as alternative generating sources is becoming a reality worldwide [1, 2]. Social and political considerations, which encourage the utilization of renewable sources, resulted in large scale deployment of Distributed Generation "DG" in power systems [3, 4]. This paradigm is motivated by the increasing concern over greenhouse gas emissions and the need for eliminating the unnecessary transmission and distribution costs [5]. Thus, it is expected that DG will have a significant contribution in electrical power systems in the near future, where small generating sources located close to load centres are dispersed in the distribution networks [5].

The utilization of DG sources inherently offers a number of technical, environmental and economical benefits for utilities and consumers due to their location close to the customer [5, 6]. Modularity, power loss reduction, improving the voltage profiles, deferring the transmission and distribution investments and offsetting the pollutant emissions represent some of these advantages. Many types of these new technologies are based on power electronic converters for grid coupling unlike conventional synchronous generators [5]. In addition, some DG units, like photovoltaic and fuel cells, are not characterized by the electromechanical energy conversion concept [5]. The special characteristics of the DG units and their low inertia can produce many technical and operating challenges regarding the stability of power systems [3, 7].

Generally, a small number of quite small-size DG units, compared to the large centralized power stations, will not influence the operation of the power network and hence their impact can be neglected. However, when networks begin to contain large numbers of DG units with higher capacities, the overall dynamics of power systems are significantly impacted [5]. Therefore, power system analysis including DG units becomes an emerging problem especially with the wide range of technologies associated with DG units and the configuration uniqueness of each distribution network [3].

The most favourable types of DG technologies installed at consumer sites are those providing combined heat and power generation. Therefore, conventional fossil-fuel generators are candidates as DG units to be utilized in large scales in the near future, which would achieve the prospective reduction in the investment costs [4]. Two different DG technologies, namely fuel cells and micro turbines, can be considered as promising sources either as individual units or in the hybrid configuration [8]. Hence, the performance and characteristic of modern power systems comprising large numbers of such DG units have to be analyzed.

Among the numerous issues related to power systems containing DG units and that need investigation, stability analysis and assessment of the adequacy damping of the oscillatory behaviour is of major interest [1, 3, 5]. The conventional approach, which depends on representing DG units together with passive loads in an aggregated form or omitting their effect when analyzing power system stability, is about to change [1, 9]. Modern power systems are mostly operating close to their stability limits for economical reasons. This situation demands accurate modelling of power systems taking into consideration the different penetration levels of DG units to adequately evaluate their impacts on the stability of power systems.

The objective of this paper is to investigate the impact of utilizing selected DG units with different penetration levels on the various forms of power system stability. To evaluate the impact with considerable contributions of the dispersed units, a hypothetical power network with two main centralized power plants and several DG units connected onto the electric distribution system is investigated. In this study, certain numbers of DG units are switched on to supply the required power range of 0.0% to 28.3% of the total load demand in the distribution network. With each penetration level, the stability of the network is studied and compared to the case of supplying the load fully from the conventional power plants as a reference case. This can help in evaluating the influence of the large scale utilization of DG in electrical power networks.

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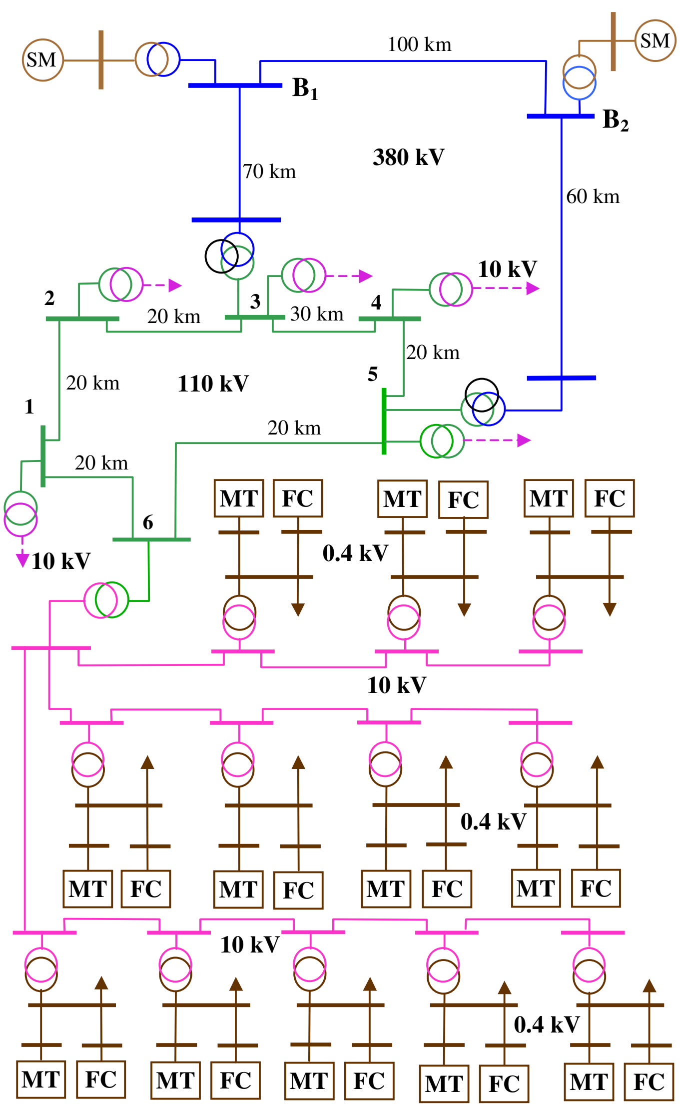
II. Power System Description

The electrical network under consideration comprises a high-voltage area with two voltage levels, namely 380kV and 110kV. As centralized power plants, two synchronous generators are simulated and connected to the 380kV nodes via step-up transformers. Six typical distribution networks are simulated and integrated into the network through six buses in the 110kV area using 110/10kV transformers. In addition, distribution transformers are used to step-down the voltage to the 0.4kV level at each load centre. A total number of 56 end-user terminals are simulated with different load-demand levels. The total active load demand in the network is about 250MW. Fig. 1 illustrates the one line diagram of the network showing only one distribution system with the DG units integrated near the load centres. The other five distribution networks have similar configurations like that shown in the figure. The modelling and simulation of the network are accomplished using the simulation package "*Power System Dynamics* (PSD)" [10].



Buses 1 to 5 are extended to the low voltage area with similar integration of Micro-Turbines (MT) and Fuel Cells (FC) like that shown for bus 6

Fig. 1. The one line diagram of the electrical network showing the integration of fuel cells and micro-turbines near the end user terminals

Two types of DG technology are considered as dispersed sources: fuel cells and micro-turbines. A fuel cell and a micro-turbine are placed in locations near each load centre and connected to theses nodes using 50m to 250m cables. This configuration allows supplying the loads partially from the DG sources with different generation levels, while the remainder is covered by the two synchronous generators supplying into the high voltage network. Table 1 summarizes the number of components in the investigated network.

Table 1. The number of components in the investigated network

Synchronous generators	Buses	Branches	Transformers	Fuel cells	Micro-turbines
2	245	180	66	56	56

The selected locations of DG units near the load centres are expected to achieve some improvements in the voltage profiles of the distribution network. With the latest static converters, the utilization of the DG units could achieve the required voltage support in the distribution network. This can be accomplished by regulating the reactive power through the adjustment of the power factor of converters based on the voltage level on local nodes [2]. On the other hand, tap-changing transformers will not be suitable for the effective regulation of the voltages at all feeder nodes as they assume decreasing voltages along radial feeders [2, 4]. In addition, the voltage regulators will not correctly measure feeder demands, rather, the observed loads will be lower than actual values due to the onsite generated power in the DG units. The use of DG units will also decrease the overall power losses due to the reduction of the power transmitted from the high-voltage network.

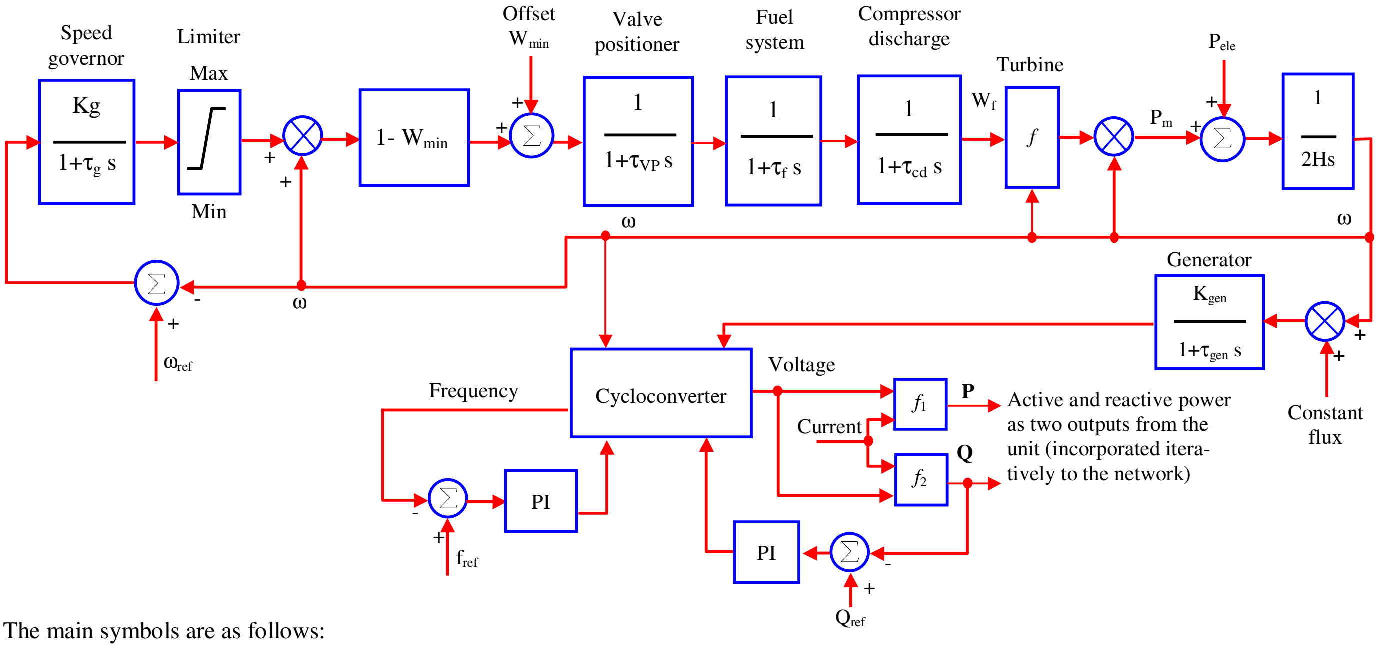
The contribution level of the DG units is defined by switching on a number of them at different feeders to give the required power. In all simulated cases, both active and reactive power demand of the loads are kept constant. Thus, the power required from the two synchronous generators decreases with the increase of the penetration level of the DG units in the network. Some details about the modelling of power sources in the network are given in the following sections.

A. Synchronous generators

Typical parameters of thermal units are used to simulate the two synchronous generators using fifth-order models with a rated voltage of 15.75kV. IEEE standard regulators are used for modelling the speed governors and the excitation systems. Since the required power from the generators varies with the variation of the DG power, the rated MVA of the two generators is also changed in each case starting from 110MVA with the 28.3% penetration level up to 150MVA without DG units. The reserve power of each generator is assumed to be always 10% of the rated value and hence, it is proportional with the nominal power. Consequently, the two generators will provide higher reserve power when they are used to fully supply the load due to their higher rating. In each investigated case, the reactive power of each generator is adjusted to obtain the same power factor like that without DG units.

B. Micro-turbines

Fig. 2 shows the block diagram of the micro-turbine dynamic model.



The main symbols are as follows:

H	:	inertia constant
K_g, K_{gen}	:	gains of speed governor and generator respectively
τ_g, τ_{vp}, τ_f, τ_{cd}, τ_{gen}	:	lag-time constants of speed governor, valve positioner, fuel system, compressor discharge and generator respectively
P_{ele}, P_m, P_{th}	:	input-electrical, mechanical, and thermal power respectively
Q_{ref}, f_{ref}, ω_{ref}, P_{ref}	:	reference reactive power, frequency, angular speed, and thermal power respectively.

Fig. 2. Model of the micro-turbine generating unit

The three main parts of the micro-turbine unit are: the compressor, the combustor, and the turbine. The compressor is used to pressurize the air before entering the combustor. Injected fuel is mixed with the compressed air in the combustor and the mixture is ignited. Mechanical energy is produced when the hot combustion gases flow and expand through the turbine. The turbine drives a permanent magnet synchronous generator (PMSG) connected to its shaft without gearbox. A part of the power produced in the turbine is utilized for driving the air compressor while the rest is converted into electricity in the PMSG.

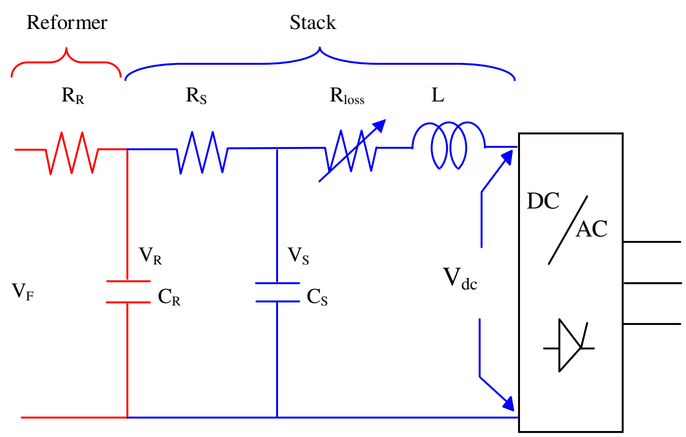
Since the frequency of the generated power from the micro-turbine is very high, a cycloconverter is required to reduce this frequency to the standard levels. The cycloconverter is used not only to get normal frequency but also to regulate the unit reactive power. Two PI controllers are employed to regulate the frequency and the reactive power of the unit. The PMSG is represented in this study by a simple first order model. The offset (W_{min}) in the figure represents the fuel demand at no-load condition. The following function is used to simulate the performance of the turbine:

$$f = 1.3(W_f - W_{min}) + 0.5\,(1 - \omega) \qquad (1)$$

The ratings of the 56 micro-turbine units simulated in this study vary between 0.3MW and 0.8MW.

C. Fuel cells

The fuel cell has three main parts, which are the reformer, the stack, and the power conditioner. The reformer produces a hydrogen-rich gas, which is processed in the stack with air to produce water and heat. As a result of this electro-chemical process, a DC power is produced in the stack. The generated DC power is converted to AC power through the power conditioner. The processes are accomplished at high efficiency since the fuel cell has no moving parts. For the stability studies, a third order non-linear equivalent circuit dynamic model is proposed to approximate the fuel cell dynamics as seen from the network side. Fig. 3 illustrates the proposed equivalent circuit describing the dynamics of the fuel cell units [8].



The main symbols are as follows:

V_F	:	input reversible voltage (also represents the input fuel rate)
V_R	:	output from the reformer (input to the stack)
V_{dc}	:	output DC voltage from the stack
R_{loss}	:	nonlinear-loss resistance

Fig.3. Dynamic equivalent circuit model of the fuel cell

The delay actions in both the reformer and the stack are represented as first-order time delay elements. However, the time delay of the reformer is much longer than that of the stack [11]. To simulate the steady-state characteristic of the fuel cell, a non-linear resistance is used to represent all kinds of voltage drops in the stack. This resistance is obtained from the voltage-current characteristic of the fuel cell at steady state. It can also be calculated using the Nernest and Butler-Volmer equations [8]. A non-linear function is developed using the curve fitting technique to derive the resistance as a function of the supplied current. Also an inductor is inserted taking into account the time constant associated with the current. A DC-AC pulse-width modulation (PWM) inverter is used to convert the DC power from the stack to AC power. During the conversion of the power, both the frequency and the reactive power of the fuel cell are regulated.

The time constants of the reformer (τ_R) and the stack (τ_S) are given in terms of the equivalent-circuit parameters by the following equations:

$$\tau_R = R_R\, C_R \qquad (2)$$

$$\tau_S = R_S\, C_S \qquad (3)$$

In these equivalent circuits, the time constants vary in the range of 1.0-2.0s for the reformer and 0.08-0.18s for the stack depending on the ratings of the unit. Typical V-I characteristics are used to develop the loss-resistances as functions of the supplied currents for different types of fuel cells. This includes the Proton Exchange Membrane (PEMFC), the Alkaline (AFC), and the Solid Oxide (SOFC) types [8]. The ratings of the 56 fuel cells vary in the range of 0.5MW up to 1.0MW.

Since most of the DG units are not utility owned, the power supplied from these units will be defined according to economic consideration. Therefore, it is assumed in the simulation that the power from the DG units will not be adjusted to follow up the load demand. Rather, the owner of the DG unit will supply a specific value of the power to achieve the maximum profit regardless of load changes.

For secure operation, the DG units are assumed to be disconnected from the network if the voltages at their terminals decrease below 80% of their rated values. This is important to protect the power electronic converter with these units. A delay time of 100ms (five cycles) is assumed for measurements and disconnection of any DG unit after reaching the critical limit. The disconnection of some of the DG units during the simulation represents an additional disturbance to the network. Once any unit is switched off, it is not connected again since the simulation time is smaller than the time required for accomplishing the conventional procedures for the reconnection.

III. Angle Stability Analysis

A. Oscillatory stability

The interconnected power systems are continually subjected to small disturbances such as changes in loading conditions. The oscillatory behaviour of the network following such disturbances depends on the operating condition, controller settings and the structure of the network [3]. Due to economic considerations, the electrical power networks are commonly operating near the stability limits. Therefore, oscillatory stability is attracting more interest and its analysis is essential for power system security. The oscillatory instability occurs usually due to the insufficient damping of the electromechanical oscillations. To assess the oscillatory stability of electrical power networks, the modal analysis is employed since it represents the most common approach in this field [3].

With each of the seven penetration levels of the DG units, a power flow computation is carried out to define the operating condition of the network. Modal analysis is then performed for the network in each case and the results are compared. A special interest is directed to critical modes, which have low damping ratios. Fig. 4 illustrates the critical eigenvalues with different power contributions from DG units in the "s" plane. Due to the similarity, only eigenvalues with positive frequency are shown.

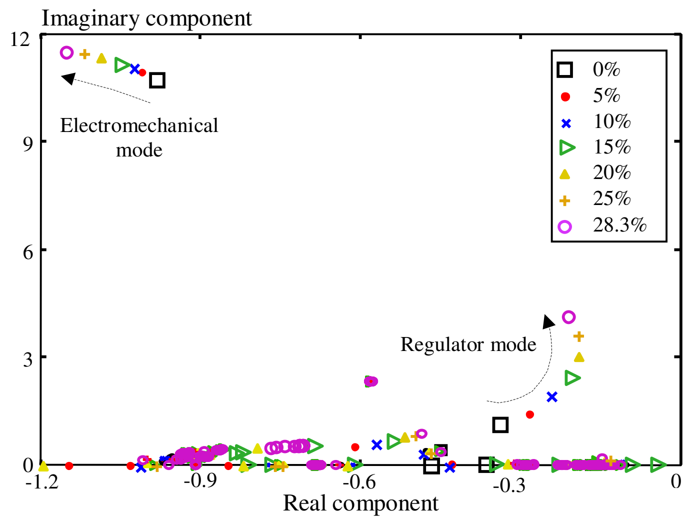


Fig. 4. Critical eigenvalues with different power contributions from DG units

From the modal analysis, two critical modes can be recognized. The first one represents the electromechanical mode. With the insertion of more DG units, the damping of this mode is slightly improved and the corresponding frequency is increased. On the other hand, the second mode is more affected by the utilization of power from DG units. This mode belongs to the regulators of the synchronous generators. The utilization of the DG units causes lower damping and higher frequency for this mode. However, it seems that further utilization of DG units can then improve the damping factor of this mode. This would be caused by the interaction between the controllers of the synchronous generators and those of the DG units. With small numbers of DG units near some of the load nodes, the DG controllers have only local action and the global damping of the controller mode is worsened. The use of a large number of DG units, which are uniformly dispersed in the low voltage area, extends the controller action to cover most of the load nodes. Hence, the performance of this mode is slightly improved with the high penetration levels of the DG units.

For more details, table 2 gives more information about the two most critical modes associated with the seven penetration levels.

Table 2. Critical modes with different power contributions from DG units

Penetration level	Electromechanical mode		Regulator mode	
	Eigenvalue	Damping factor	Eigenvalue	Damping factor
0.0%	-0.984±j10.774	9.095%	-0.340±j1.579	28.179%
5.0%	-1.009±10.933	9.188%	-0.294±1.397	20.607%
10.0%	-1.028±11.081	9.239%	-0.272±1.702	15.785%
15.0%	-1.052±11.204	9.347%	-0.240±2.092	11.377%
20.0%	-1.086±11.341	9.530%	-0.221±2.602	8.465%
25.0%	-1.118±11.471	9.702%	-0.222±3.122	7.086%
28.3%	-1.153±11.524	9.959%	-0.242±3.685	6.546%

B. Transient stability

Transient stability issues, also referred to as the first swing stability, are among the most important practical concerns in power system operation and planning studies. The assessment of transient stability, where the angle stability under large disturbances is investigated, is becoming an essential requirement for the security of electrical power systems. It is defined as the ability of the power system to maintain synchronism when subjected to a severe disturbance such as short circuits or loss of large loads or generation. Transient stability depends on the initial operating conditions of the system as well as the type, severity and location of the disturbance [12].

The common methods for transient stability assessment are based on the time-domain simulations and the analysis of the transient energy function, which corresponds with the extended equal area criterion under some assumptions [13]. In this paper, time-domain simulation technique is employed to assess the impact of DG penetration level on the transient stability of the power system. Here, the power angle between the two synchronous generators has been chosen as an indicator to assess the transient stability.

To investigate the transient stability of the test system, two 150ms self-clearing three-phase through fault impedance short circuits are simulated. The first one is at bus “B1”, while the second one is at bus “B2” (see Fig. 1). It is assumed that no parts of the network are disconnected during the applied faults. As a result of the first fault, the voltage level at the terminals of all DG units did not reach the 80% limit and hence, no DG unit is disconnected. Fig. 5 shows the responses of the power angle between the two generators to this disturbance.

On the other hand, some DG units are switched off as a consequence of the second fault due to the voltage decrease lower that the 80% limit. The disconnection of these units causes a loss of generating sources, which forces the network to operate at a new operating point. Fig. 6 illustrates the change of the angle deviation between the two synchronous generators with different penetration levels of the DG units.

From the observation of the first swing, it is evident how the utilization of DG units reduces the magnitude of the maximum power-angle deviation. This indicates that the existence of the DG units improves significantly the transient stability of the system. This also means that the increase of the penetration level of DG units within power systems provides the opportunity to handle larger disturbances. In some critical cases and with more severe faults, the use of DG units can maintain synchronism due to the reduction of the maximum power-angle deviation between generators.

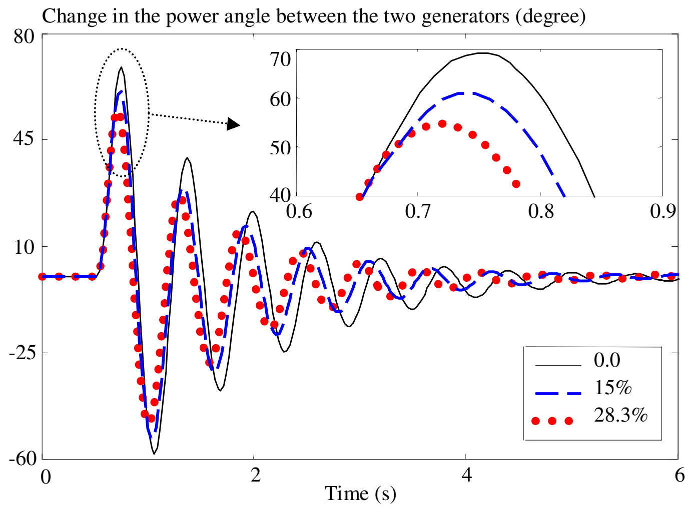


Fig. 5. Variation of the power angle between the two generators due to a fault in the high-voltage network: case 1, no DG unit is switched off

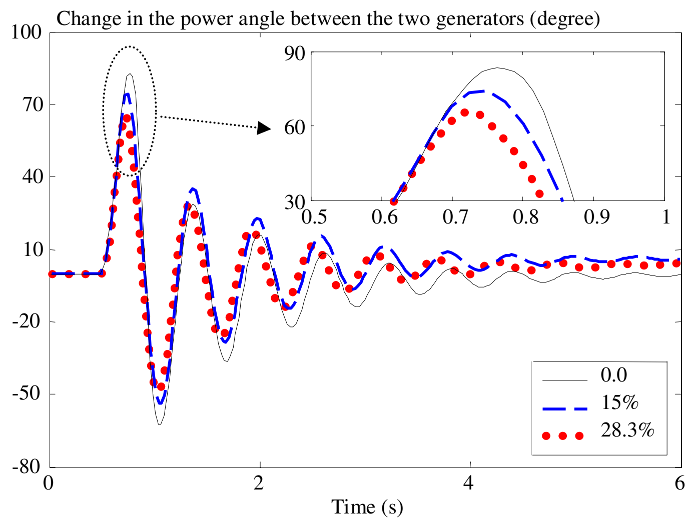


Fig. 6. Variation of the power angle between the two generators due to a fault in the high-voltage network: case 2, some of the DG units are switched off

Due to the loss of some DG units in the second case shown in Fig. 6, the power angle between the two generators reaches a new steady-state value after the fault clearance depending on the contribution of each generator to compensate for the loss of power due to the disconnection of the DG units.

As expected from the modal analysis, the response shows higher frequency and somewhat increased damping when more power from DG units is used. This additional damping of the oscillations achieved when utilizing the DG units reflects the improvements in the post-fault performance of the network.

IV. Frequency Stability Analysis

Following large disturbances in power systems, significant imbalance takes place between generated power and load demands. Furthermore, imbalances occur between the electromagnetic and the mechanical torques of the generators. The consequential accelerations or decelerations of generators due to this imbalance result in changes in the frequency of the network, which can impact the stability of the system. Frequency stability refers to the ability of electrical power systems to maintain fixed frequency after being subjected to a severe disturbance [12]. The frequency will not cause a stability problem if the equilibrium between generation and load is restored. This requires sufficient generation reserve and adequate response from the control and protection devices. If the disturbance results in sustained frequency oscillations, generating units will be sequentially tripped out of the network and the stability will be lost.

To examine the frequency response of the network after severe disturbances, a 10MW load is switched on in the high-voltage network and the frequency response of the network is observed. The load is switched on at bus B_2 (see Fig. 1). Fig 7 shows the frequency response of the network to the abovementioned disturbance. A comparison between the network performance without DG units and with 15% and 28.3% contributions from these units is given in the figure.

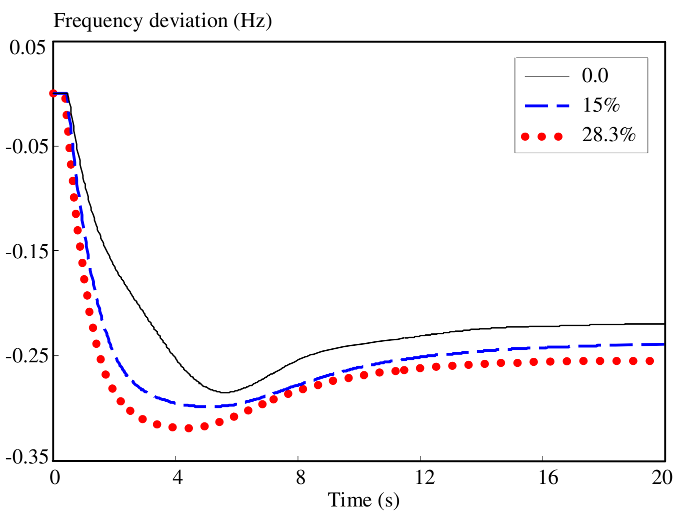


Fig. 7. Frequency deviation as a result of a 10MW (~6% of the total power generation) load switching in the high-voltage network

In all cases, the network succeeded to maintain new steady frequencies after load switching. In the case of supplying the load fully from the synchronous generators, the generators provide more absolute reserve power to the network (notice that the percentage reserve power is always constant at 10% of the rated power). This explains the increase of the maximum frequency deviation when more power form DG units are utilized, which means lower rating and consequently lower absolute reserve power from the synchronous generators. It is therefore suggested to increase the percentage reserve power of the synchronous generators when DG units are utilized to maintain the total absolute reserve power of the network at acceptable levels.

On the other hand, the inertia constant is lower with the increase of DG units due to the decrease of the rated power of the rotating synchronous generators. Thus, faster frequency response can be obtained in the transient period when DG units are used. Therefore, the minimum frequency level is reached faster than the case without DG units.

V. Voltage Stability Analysis

Voltage stability is defined as the ability of a power system to maintain the voltages at all nodes within acceptable limits after being subjected to a disturbance [12]. Voltage instability results from the progressive collapse or rise of voltages of network nodes, which may cause the loss of some loads or transmission lines. The tendency of induction motors to restore their power after disturbances by adjusting their operating slips would increase the reactive power consumption causing further voltage reduction. If the required power consumption by loads is beyond the capability of the generators or transmission systems, a run-down situation causing voltage instability takes place.

The voltage stability of the investigated network is tested by applying some disturbances in both the high and the low-voltage networks. Fig. 8 shows the voltage response to the abovementioned 150ms fault at bus (B_2). All DG units contain suitable reactive power controllers to regulate their performance. Since these units are located near the load centres, some improvements in the performance are achieved especially for the load during the short circuit.

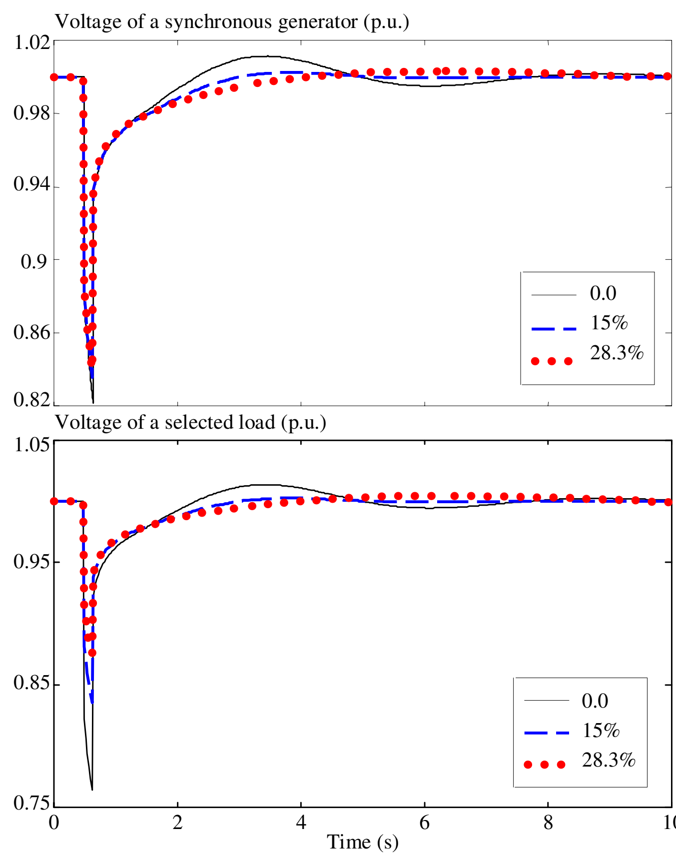


Fig. 8. Voltage variation of one of the synchronous generators and a selected load as a result of a three-phase fault in the high-voltage network

Fig. 9 illustrates the voltage response to a 10Mvar load switching at bus (B_1) in the high-voltage network (see Fig. 1). The increase of the penetration level of the DG units causes more damping to the voltage in both the low-and the high-voltage parts. In addition, lower steady-state voltage deviations are achieved at load terminals when the DG sources are used near of them. However, the steady-state voltage deviations at the generator terminals are lower when no DG units are used. Due to the higher capacity of synchronous generators without DG units, they can achieve better local voltage support at their terminals. Therefore, the synchronous generators compensate the reactive-load switching with lower terminal-voltage deviations.

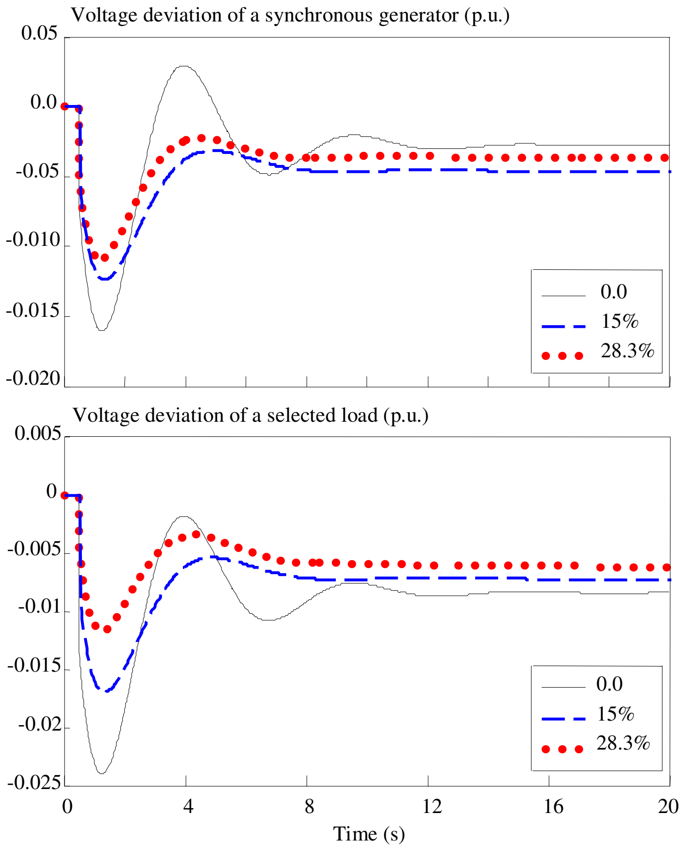


Fig. 9. Voltage deviation of one of the synchronous generators and a selected load as a result of switching a load of 10Mvar in the high-voltage network

Fig. 10 shows the voltage deviation at two load nodes when a load of 1Mvar is switched on at the terminals of the first load of them. The second load node is about 2km away from the switching point. A large voltage decrease occurs at the switching point when the DG units are not utilized. This voltage decrease is significantly reduced when the 28.3% penetration level is considered. The other load terminals in the distribution system incorporate also some improvements in the voltage profiles when DG units are used. The voltage decrease and the relative improvements in the voltage profiles at these terminals vary depending on their relative locations with respect to the switching point.

Generally, the analysis of the system performance with regard to voltage stability shows that DG can support and improve the voltage profiles at load terminals. This can extend the stability margin of dynamic loads, i.e. induction motors, which can lose their stabile operating point with large voltage dips.

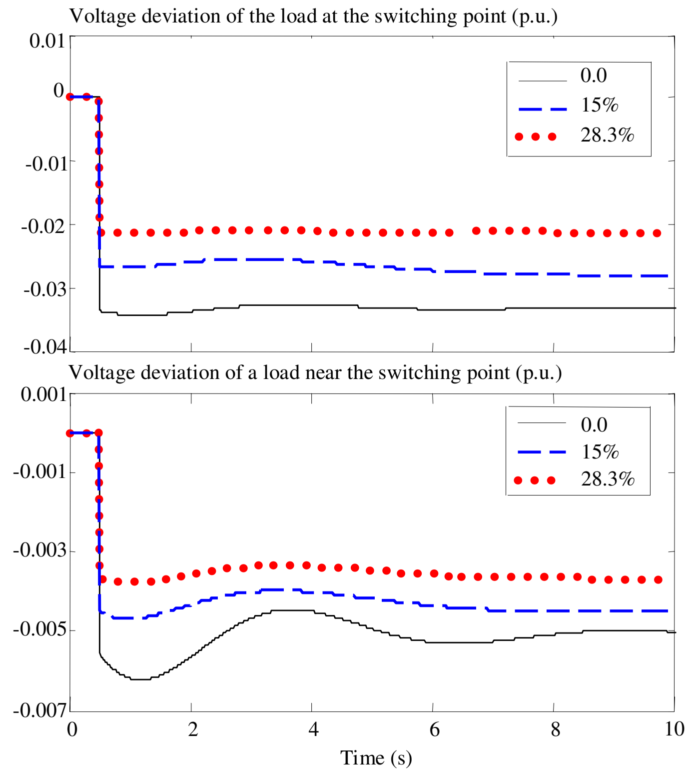


Fig. 10. Voltage deviation at two load terminals as a result of a switching a load of 1Mvar in the low-voltage network

VI. Conclusion

This paper addresses the impact of DG with different penetration levels on the stability of power systems. A hypothetical network with two conventional power plants and many DG units is simulated. Based on the results and discussion, it can be concluded that DG can improve the stability of power systems if suitable types and appropriate locations are selected. Regarding the oscillatory stability, the utilization of DG improves the damping of the electromechanical modes and slightly increases their frequency. This fact is confirmed through the time-domain simulation of some disturbances. The transient stability analysis shows that the maximum power-angle deviations between the generators are decreased with the increase of the penetration level of the DG units. However, the disconnection of some DG units when the voltage decreases below 80% of the nominal value represents an additional disturbance to the network.

With more power from the DG units, the absolute reserve power from synchronous generators and the network inertia constant are smaller due to the lower rated power of the rotating synchronous generators. As a result, the frequency response shows faster behaviour with higher maximum-frequency deviations when more DG units are employed. The voltage profiles at load terminals are also improved due to the use of active DG sources near end-user terminals. The controllers designed to regulate the performance of the DG units participate also in improving the voltage stability of the network. To maximize the benefits of utilizing DG units, the stability of the individual DG units themselves has to be improved to ensure their continuous and reliable operation to provide effective support to the stability of the entire network.

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VIII. BIOGRAPHIES

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