Industrial Networks Performance Enhancement Using Fuzzy Controlled Distributed Generation

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Abstract –Induction Motors (IM) are one of the main and voltage sensitive loads within industrial centers whose start-up and loading characteristics affect the nearby loads adversely. The performance of induction motors is influenced by their supply voltage; thus, such faults as short circuits can lead to their instability. Distributed Generation Units (DGUs), recently applied by electric utilities and consumers with a remarkable growth, can provide the desired active power based on a proper control algorithm and configuration of such voltage source converters as parallel, series and hybrid in one hand, and compensate for various power quality and voltage regulation problems, on the other; hence so called Flexible Distributed Generation (FDG). In this paper, a new interface is introduced for connecting DGUs to the distribution network. The proposed interface is not only able to provide some portion of active power to loads, but also maintains the nominal voltage for a wide range of operational conditions. Hence, it can replace such compensation devices as Distribution Static Compensators (D-STATCOM) or On-Load Tap Changer transformers (OLTC), which have already being used for voltage regulation of distribution networks. Within the interface, a fuzzy controller is used for the voltage control loop. Computer simulation in MATLAB-Simulink proves the performance enhancement of the interface

Keywords: Induction Motors, Voltage Control, Distributed Generation, Fuzzy Control, Active and Reactive Power Control

I. Introduction

Industrial networks usually include loads sensitive to supply voltage whose operational characteristics can affect the nearby loads adversely. Induction motors (IMs) are among the main loads of industrial networks with a highly sensitive start-up and loading characteristics to the common point voltage which may lead to their instability and thus, unsuccessful operation of the nearby loads, too, in case of a poor network. Also, during the fault occurrence, they might be unstable. Therefore, the voltage regulation of the common point of industrial loads for a broad range of operational conditions is a necessary and vital action [1-7].

In order to avoid the motors instability and provide the normal operational conditions, there have been used such methods as Bus Transferring [8], resistance insertion into the rotor circuit, speed regulation drives and voltage drop prevention upon fault occurrence. The voltage transferring causes electrical stress for the network especially for motors, while resistance insertion into rotor is not applicable to squirrel-caged motors. The speed control derives are not cost effective especially for higher powers. To prevent the voltage drop during fault times, tap control within transformers, reference bus voltage control and reactive power compensation can be used. Voltage compensation using transformer taps is stepwise, limited and slow. The reference bus voltage control, also, is not possible in load centers. The power reactive compensation, however, is a convenient and applicable alternative for voltage drop prevention [9-10].

Distributed Generation (DG) is defined as an electrical power source which are connected to the distribution network directly [11]. Through the last decades, there has been a remarkable growth in using Distributed Generation Units (DGUs) by electric utilities and consumers. Electric utilities consider DG as a necessary element which can replace the new power stations to respond to the increasing demand of electricity [12]. The application of DG in the total power generation has been predicted to rise to 25-30 percent until 2020 [13-14]. Inserting DGUs into distribution network bring about technical as well as environmental and economical advantages [15].

The present DGUs are usually used to provide distribution network or consumers with active power; they use voltage source converter as an interface to the network. To the author's best knowledge, until now, the most of researchers' attention have been focused on the DGUs interface for active power provision and less attention has been paid to their capability in reactive power compensation and thus, performance enhancement of industrial networks [16-17]. In this paper, a new interface is introduced for connecting DGUs to distribution network. The proposed interface not only provides some portion of active power to the loads, but also maintains the nominal voltage for a wide range of operational conditions; hence it

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is called Flexible Distributed Generation (FDG). For the voltage control loop, a fuzzy controller is used which is characterized as a robust and insensitive to the system operational parameters. The advantage of the fuzzy controllers is resulted of their capability in nonlinearity behavior management of physical systems with complex structures based on expert knowledge about the process under control. Besides, fuzzy controllers are inherently adaptive and insensitive to parameter variations and do not need mathematical models. The voltage source converter used here is a three-phase two-bridge inverter which decreases the harmonic content and thus, needs a smaller filter on its AC side compared to the three-phase bridge inverter [18]. The new interface can replace such compensation devices as Distribution Static Compensators (D-STATCOM) or On-Load Tap Changer transformers (OLTC), which have already being used for voltage regulation of distribution networks. For the purpose of performance evaluation, the computer simulation in MATLAB-Simulink is used.

This paper is divided into 5 sections. In the following section, the system under study is introduced, the voltage source converter configuration is characterized and the control algorithm for both the desired active power generation and voltage regulation is presented. The fuzzy controller design for voltage regulation is explained in section III. Section IV presents the computer simulation results and finally, section V concludes the paper.

II. System Description

Fig. 1 shows the single line diagram of the system under study along with FDG. Here, the 25 KVs source with Short Circuit Capacity (SCC) of 1000 MVA supply the static and motor loads at 2.4 KVs through two feeders. More information on the systems can be found in appendix.

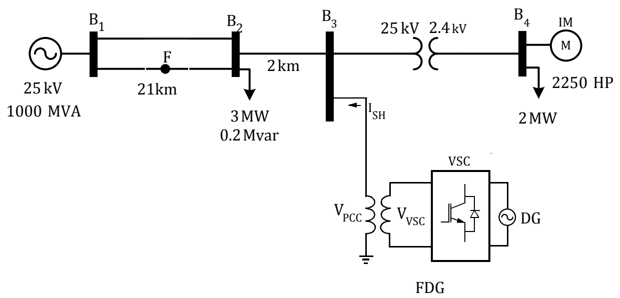

Fig. 1. Single line diagram of the system under test with FDG

A. Voltage Source Converter Configuration

The voltage source converter that connects the DC network- the DC voltage produced by DG- to AC network through a coupling transformer (fig. 1) is combined of two two-level three-phase bridge inverter, as shown in fig. 2. This configuration produces less harmonics compared to a three-phase bridge inverter and thus, requires a smaller filter on its AC side; it also provides higher voltage gains [18].

The supplied voltage on the primary side of transformer,Tr_A, is obtained as follows:

$$v_{w1}(t) = mV_{dc}\sin(\omega t + \varphi_{w1}) \qquad (1)$$

where m is the modulation index, φ_{w1}, the voltage phase angle. The active and reactive powers at the outputof inverters are controlled through appropriate switching.

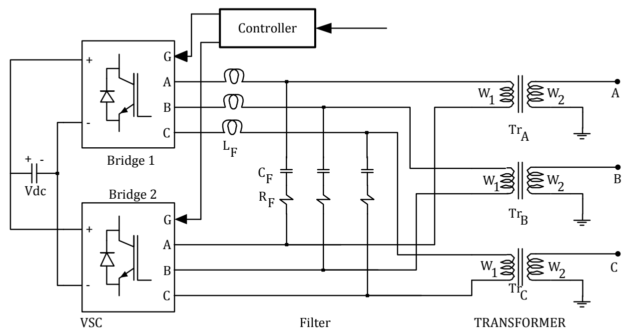

Fig. 2. Voltage source converter configuration

B. Control Algorithm

DG is connected to the distribution system by means of the voltage source converter, as shown in fig. 1. Based on the desired active power, P_{Ref}, and required reactive power for the voltage regulation of common point, V_{PCC}, the voltage source converter is controlled through the current. Fig. 3 illustrates the phasor diagram of source current, load current and FDG current for the steady state in dq synchronous rotational reference frame. Coinciding the d axis of reference frame with the common point voltage of FDG, V_{PCC}, the d and q current components of FDG, $I_{SH,d}$,$I_{SH,q}$ will contribute to the provision of, respectively, the required active power and the reactive power for the voltage regulation of common point at reference value $V_{PCC,Ref}$.Considering these voltage and current amplitudes as the base values for the corresponding parameters, the injected active power of FDG will be:

$$P_{SH} = V_{PCC,d}I_{SH,d} + V_{PCC,q}I_{SH,q} \qquad (2)$$

Assuming $V_{PCC} = V_{PCC,d}$ or $V_{PCC,q} = 0$, the reference current $I_{SHd,Ref}$ is determined. That is:

$$I_{SHd,Ref} = \frac{P_{Ref}}{V_{PCC}} \qquad (3)$$

The $V_{PCC,d}$ and $V_{PCC,q}$ can be calculated through transferring of the phase voltage of common point, $V_{PCC,a}$, $V_{PCC,b}$, $V_{PCC,c}$, to the synchronous reference frame using the following equations:

$$V_{PCC,d} = \frac{2}{3}\left(V_{PCC,a}\sin(\omega t) + V_{PCC,b}\sin(\omega t - 2\pi/3) - V_{PCC,c}\sin(\omega t + 2\pi/3)\right)$$

$$V_{PCC,q} = \frac{2}{3}\left(V_{PCC,a}\cos(\omega t) + V_{PCC,b}\cos(\omega t - 2\pi/3) - V_{PCC,c}\cos(\omega t + 2\pi/3)\right) (4)$$

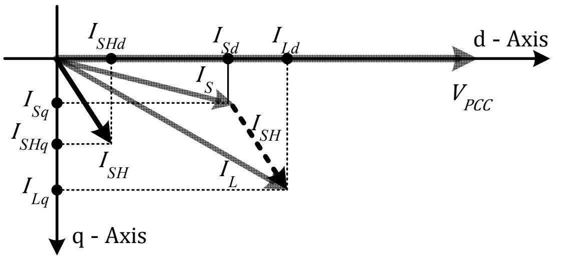

Fig. 3. Phasor diagram of FDG and load currents in dq reference frame

whereωt will be obtained from the common point voltage by means of a phase-locked-loop (PLL) (fig. 4) and will be used for calculation of the direct and quadrature components of the three-phase voltages. The d and q components of the three-phase current will be obtained using a similar equation as (3) for currents.

The injected or absorbed reactive power of FDG can be obtained as:

$$Q_{SH} = -V_{PCC,d} I_{SH,q} \qquad (5)$$

Due to the variation of V_{PCC} in different operational conditions in one hand, and nonlinear behavior of induction motors on the other, a fuzzy controller is used for determining the reference current $I_{SHq,Ref}$. Fig. 4 shows the block diagram of the voltage source converter control system. The main elements of the block diagram are PLL, AC measurement, fuzzy controller for common point voltage control and current controller VSC. The PLL is used for transferring three-phase system variables into synchronous rotational reference frame and AC measurements for measuring d and q components of positive sequence voltages and currents. The current controllers, used for determining the d and q components of VSC (amplitude and angle), are Proportional-Integrator (PI) controllers.

III. Fuzzy controller design for voltage regulation

The inputs to the fuzzy controller are the scaled values of voltage error $V_{PCC,e}$ and its derivative $\dot{V}_{PCC,e}$ obtained by the followings:

$$V_{PCC,ac} = \sqrt{{V_{PCC,d}}^2 + {V_{PCC,q}}^2} \qquad (6)$$

$$V_{PCC,e} = \left(V_{PCC,Ref} - V_{PCC,ac}\right) \qquad (7)$$

$$\dot{V}_{PCC,e} = \frac{dV_{PCC,e}}{dt} \qquad (8)$$

Fig. 5 illustrates the block diagram of the fuzzy controller. In this figure, SF and GF are, respectively, the scale factor and fuzzy controller gain that play important role in controller performance and are determined in such a way that provide a fast response in one hand and maintain stability, on the other. The Limiters keep the variables within the allowable range determined according to the nominal values of converter. The output of the fuzzy controller would be the reference variation $\Delta I_{SHq,Ref}$used for adjustment of common point voltage to the desired value (1pu).

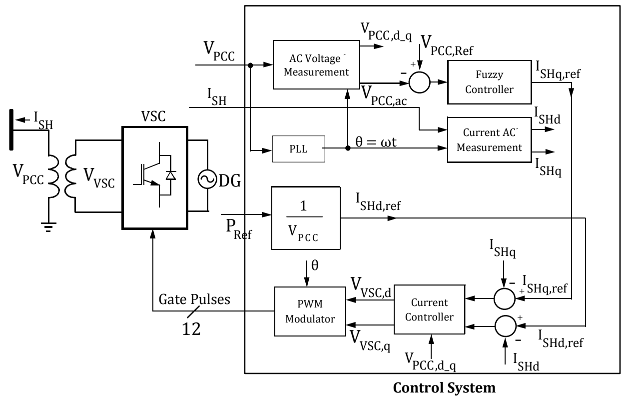

Fig. 4. The block diagram of voltage source converter control system

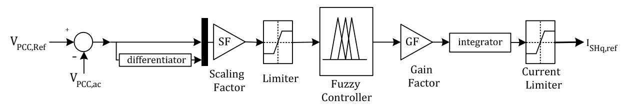

Fig. 5. The block diagram of fuzzy controller for common point voltage V_{PCC}

For the purpose of inputs fuzzification, seven Gaussian functions are used with a uniform distribution, which result in 49 rules shown in table I. all the inputs and outputs ($V_{PCC,e}$ ، $\dot{V}_{PCC,e}$and $\Delta I_{SHq,Ref}$) are fuzzy variables specified by seven language variables NB, NM, NS, Z, PS, PM and PB, respectively for big negative, medium negative, small negative, zero, small positive, medium positive and big positive.

TABLE I: RULE BASE OF FUZZY CONTROLLER

$\Delta I_{SHq,Ref}$	$\dot{V}_{PCC,e}$						
$V_{PCC,e}$	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	PS
NM	PB	PB	PM	PM	PM	PS	NS

N	F	P	P	P	P	N	N
S	B	M	M	M	S	S	M
Z	F	P	P	Z	N	N	N
	S	B	M		S	M	B
P	F	P	N	N	N	N	N
S	M	S	S	M	M	M	B
P	F	N	N	N	N	N	N
M	S	S	M	M	M	B	B
P	N	N	N	N	N	N	N
B	S	S	M	M	B	B	B

The rule base is designed such that, within the limits of FDG nominal capacity, the common point voltage reaches its commanded value without any overshoot. As an example, consider the following rule in table I:

$$IF\ V_{PCC,e}\ is\ NB\ and\ \dot{V}_{PCC,e}\ is\ PB\ THEN\ \Delta I_{SHq,Ref}\ is\ PS$$

This rule shows the conditions in which under such various causes as motors outage, V_{PCC} far exceeds the $V_{PCC,\mathrm{Ref}}$ (overvoltage), but moves towards $V_{PCC,\mathrm{Ref}}$ with high acceleration. The decision of partial increase in $\Delta I_{\mathrm{SH}q,\mathrm{Ref}}$ is to accelerate the voltage adjustment process. In order to avoid overshoots, a command signal with the following rule is required:

$$IF\ V_{PCC,e}\ is\ NM\ and\ \dot{V}_{PCC,e}\ is\ PB\ THEN\ \Delta I_{SHq,Ref}\ is\ NB$$

This rule expresses the condition in which V_{PCC} exceeds $V_{PCC,\mathrm{Ref}}$, but moves towards $V_{PCC,\mathrm{Ref}}$ with high acceleration. The decision of partial decrease in $\Delta I_{\mathrm{SH}q,\mathrm{Ref}}$ is to avoid the overshoot. The rule:

$$IF\ V_{PCC,e}\ is\ PB\ and\ \dot{V}_{PCC,e}\ is\ PB\ THEN\ \Delta I_{SHq,Ref}\ is\ NB$$

This specifies conditions in which V_{PCC} has already been far less than the reference value and still decreasing with high acceleration; in this case, the error is extremely positive with respect to the reference value; thus, $\Delta I_{\mathrm{SH}q,\mathrm{Ref}}$ must be highly positive such that the common point voltage increases. Furthermore, the rules close to the origin, i.e., $V_{PCC,e} = \mathrm{NS/PS}$ and $\dot{V}_{PCC,e} = \mathrm{PS/NS}$, whose outputs are $\Delta I_{\mathrm{SH}q,\mathrm{Ref}} = \mathrm{NS/PS}$, are used for current command changes such that error reaches zero fast. Thus, they reduce the error more effectively and improve the steady state operation of the controller. Notice that the rule base will transform any big error or change of error to a big change in quadrature current command in order to benefits from the quadrature current compensation capability of FDG. If error and its derivative becomes zero, the fuzzy controller has already reached the desired voltage command and maintains it afterwards. In case of any disturbances, the rules close to origin would change the current fast such that the effective voltage remains at the reference value. In order to derive the output $\Delta I_{\mathrm{SH}q,\mathrm{Ref}}$ from the defuzzification, the method of gravity center has been used.

Other control rules of table I have been derived with a similar reasoning. Based on the extracted rules, the decision making space would be as in fig. 6, where the relationship between control signal and input variables of controller are specified graphically.

IV. Simulation results

The system under test is shown in fig. 1. The industrial load includes a 2 MW static load and a 2250 HP motor at 2.4 KV, supplied by 2 feeders, respectively, a two-circuit 21 Km line and a 2 Km line, both coming from a 25 KV distribution substation with SCC equal to 1000 MVA. In addition to these loads, the distribution substation supplies another static load (3 MW and 0.2 capacitive MVAR) at B_2 bus. The induction motor is modeled using a seven order state space model [19]. The 21 Km feeder is modeled using a π equivalent nominal circuit and the 2 Km one as series impedance. The static loads are considered as constant power loads. The X/R of distribution substation is assumed to be 10. In fig. 1, the FDG helps to adjust the B_4 bus voltage to 1 pu and provides the B_3 bus with 2 MW active power.

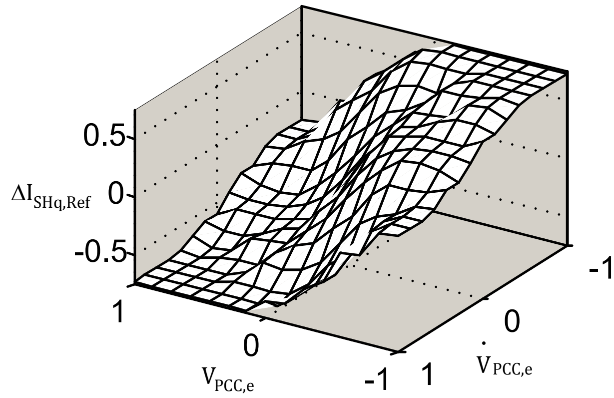

Fig. 6: Decision making space of common point voltage fuzzy controller

A. Induction Motor Start-up

Within a practical industrial network, the static loads (lighting and heating) and motors would be scheduled to enter /exit the circuit regularly. Here, we assume that the start-up of the asynchronous motors and entrance of the static loads occur simultaneously. Thus, effect of the FDG has been examined for the worst possible case.

During the start-up time, large asynchronous motors draw highly reactive current from the network which causes severe voltage drops. In case of a poor network, the start-up takes longer time that results in undesired outcomes for both motors and other network equipment. Fig. 7 shows waveforms of the industrial loads' active and reactive powers, the motor speed, the motor electromagnetic torque and buses' voltage when there is no FDG. It can be seen that in the absence of FDG, the voltage profile is not desirable; the time voltage takes to reach its steady state (start-up) is long while, at the end, it has not grasped 1pu; because of large voltage drop during start-up condition, the motor speed-up is slow. In practice, this may lead to motor damages due to thermal issues.

The presence of an FDG within the network, especially near large loads, would decrease the pulled current from the network since it provides the network with some amount of active power in one hand, and reactive power compensation at their connection point, on the other;this, in turn, prevents the voltage drop at other buses.

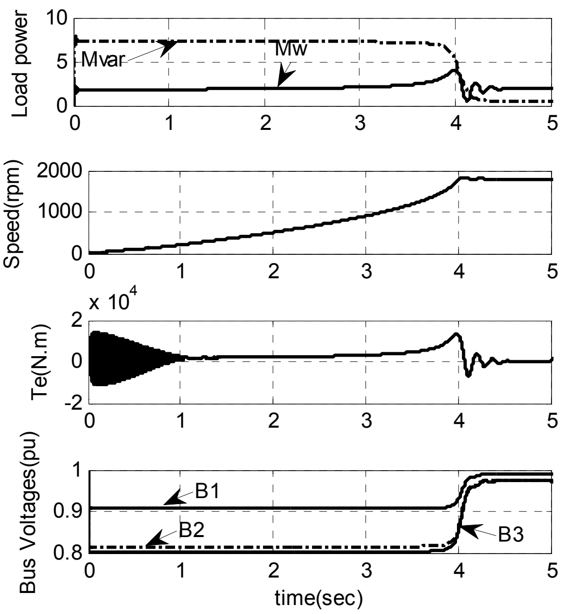

Fig. 7: Industrial load powers (MW & MVAR), motor speed (rpm), motor electromagnetic torque (Te), voltage profile of buses (pu) during start-up without FDG

Fig. 8 shows waveforms of the industrial loads' active and reactive powers, the motor speed, the motor electromagnetic torque and buses' voltages when FDG helps the network. It can be seen that presence of FDG has improved the voltage profile. Also, the voltage reaches the steady state faster and unlike the case when there was no FDG, it grasps 1pu in the end. For the case of motor speeds, again, FDG decreases the time it takes to reach the nominal speed, too. Comparison of fig. 7 with 8 reveals that the industrial loads receive more reactive power in the presence of FDG than that with no FDG, which helps to their faster start-ups. Fig. 9 depicts waveforms of the modulation index, voltage phase angle of FDG (on the converter side) and the supplied active and reactive powers of FDG.

B. Induction motor loading

Here, the asynchronous motor is assumed to be started-up and reaches the steady state without load. At t=5 seconds, a 1pu load is applied to the motor abruptly. Fig. 10 shows the motor speed and buses' voltages in case of no FDG. It is observed that the motor voltage drops after loading which, in turn, increases its current. Fig. 11 shows the motor speed and buses' voltages for the motor loading in presence of FDG. It can be seen that FDG is capable of maintaining voltage profile at 1pu. The waveforms of modulation index, voltage phase angle of FDG (on the converter side) and the corresponding produced active and reactive powers of FDG are shown in fig. 12.

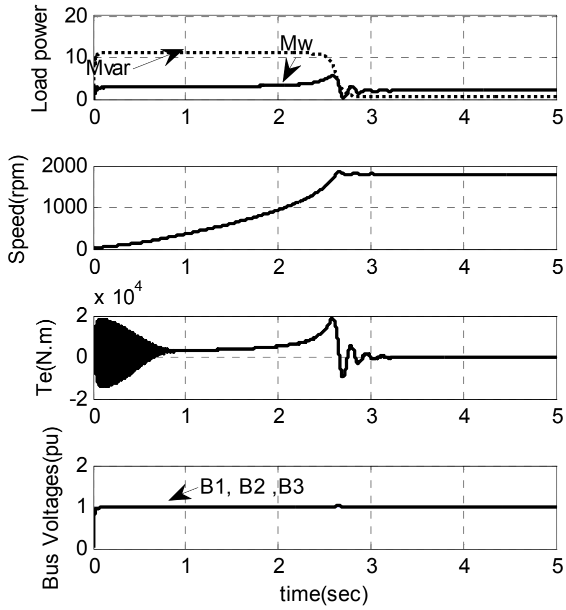

Fig. 8: Industrial load powers (MW & MVAR), motor speed (rpm), motor electromagnetic torque (Te), voltage profile of buses (pu) during start-up with FDG

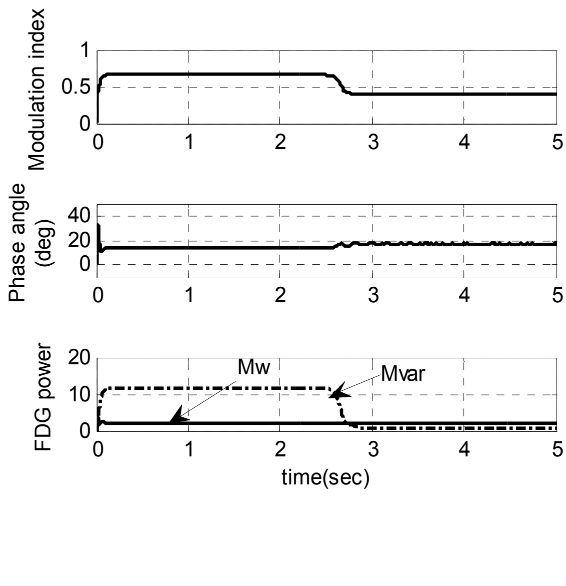

Fig. 9: Waveforms of modulation index, FDG voltage phase angel (on converter side), active and reactive power of FDG during start-up

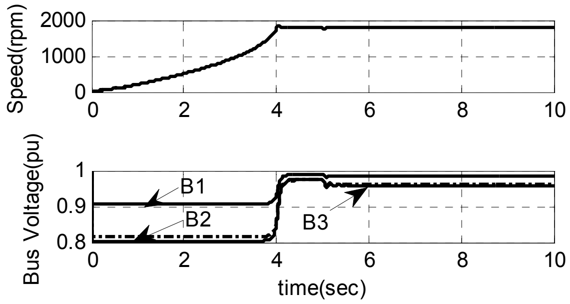

Fig. 10: Motor speed (rpm), voltage profile of buses (pu) during loading time without FDG

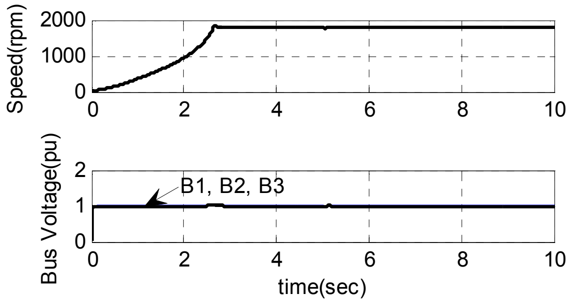

Fig. 11: Motor speed (rpm), voltage profile of buses (pu) during loading time with FDG

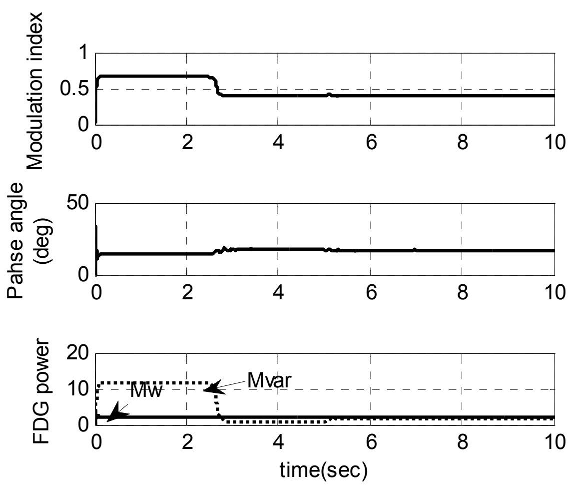

Fig. 12: Waveforms of modulation index, FDG voltage phase angel (on converter side), active and reactive power of FDG during loading time

C. Short circuit on feeder

In this section, effect of voltage drop caused by a three-phase short circuit at the middle of a line (the point F in fig. 1) is analyzed. It is assumed that the motor is in the steady state and receives 1pu power (the nominal power). Now, a three-phase short circuit occurs at the point F at t=10 seconds and is cleared at t=10.2 seconds (the fault clearing is done through line isolation). The buses' voltages and motor speed are shown in fig. 13 for the case of no FDG. It can be seen that the motor cannot return to its regular state and becomes unstable, causing a large voltage drop during the instability. Fig. 14 depicts the motor speed and buses' voltages during short circuit in presence of FDG. It can be seen that FDG helps the motor to remain stable and the bus voltage returns to 1pu shortly after short circuit clearance. The waveforms of modulation index, voltage phase angle of FDG (on the converter side) and the corresponding supplied active and reactive power of FDG through the short circuit are shown in fig. 15.

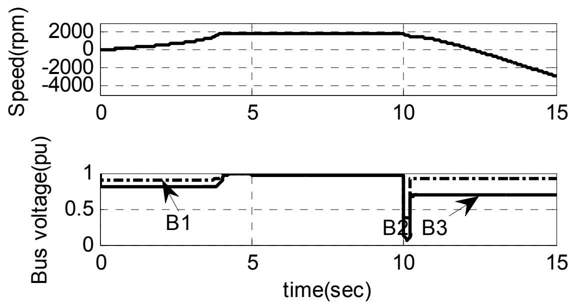

Fig. 13: Motor speed (rpm), voltage profile of buses (pu) during short-circuit without FDG

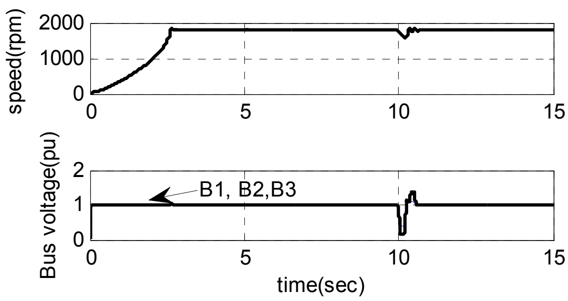

Fig. 14: Motor speed (rpm), voltage profile of buses (pu) during short-circuit with FDG

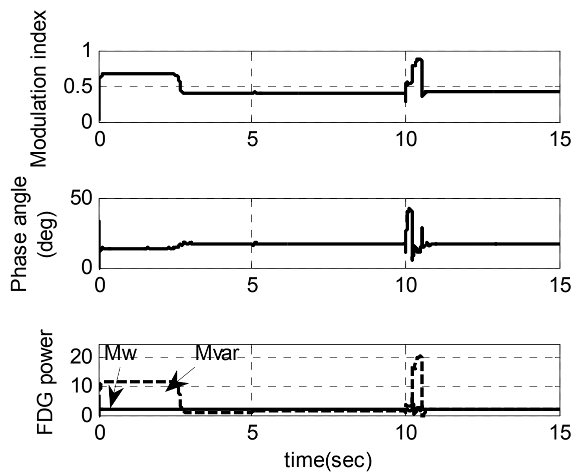

Fig. 15. Waveforms of modulation index, FDG voltage phase angel (on converter side), active and reactive power of FDG during short-circuit

V. Conclusion

In this paper, a new interface for connecting the Distributed Generation Units (DGUs) to the distribution network was proposed. The proposed interface was based on a two three-phase bridge inverter configuration in which the voltage loop control is a fuzzy controller. In addition to supplying a portion of active power, the new interface was able to adjust the voltage for a broad range of operational conditions, hence called Flexible Distributed Generation (FDG) unit. Effect of the proposed FDG on the performance enhancement of such industrial electrical loads as static loads, as well as induction motors, was investigated. For the performance analysis, operational conditions like start-up, loading and short-circuit through feeder were considered. The results of computer simulation suggests that the proposed FDG is able to provide a portion of active power in one hand, and maintains a uniform voltage profile in network, on the other; this is due to the reduction of line current and compensation for reactive power for all cases of operational states, which leads to motors stability. In the absence of FDG, it was shown that motors become unstable during short-circuit fault and the voltage profile unacceptable.

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