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The Influence of Embedded Generator Control Modes on an Electrical Distribution Network Power Flows and Voltage Profile

A. W. Azizan, *Member, IEEE* V. K. Ramachandaramurthy C. K. Loo

Abstract--**When an individual synchronous generator is remotely connected to an electrical power distribution network, the power it generates influences power flows in and out of the interconn[1]ection bus point so that the bus voltage profile varies. Voltage profile varies as the embedded generator's power reduces or increases. This variation will be illustrated by the embedded power generation modes, namely the PQ and PV modes. This paper intends to explore the effects an embedded generation modes have on an electrical power distribution system's power flows and its voltage profile by using PSCAD/EMTDC power simulation software on a selected Malaysian distribution network. The simulation result shows the embedded generation in PQ mode causing distinctive oscillation thus resulting in network voltage fluctuation.**

Index Terms-- **Distribution network; Embedded Generation; Generation Modes; PQ Control; PV Control; Power Flow; Voltage profile.**

I. NOMENCLATURE

EG	Embedded Generator
PQ	Constant real and reactive power mode
PV	Constant real power and constant voltage mode
PoC	Point of connection
SSEG	Small scale embedded generators
p.f.	Power factor
AVR	Automatic Voltage Regulator
OLTC	On-load-tap-changer
IPP	Independent power producer
MW	Megawatt or real power
MVAr	MegaVAr or reactive power
p.u.	per unit
P_EG	Active power from EG
Q_EG	Reactive power from EG
P_Grid	Active power from the utility site
Q_Grid	Reactive power from the utility site
P_Load	Active power of local load
Q_Load	Reactive power of local load

II. INTRODUCTION

EMBEDDED generation study has increased enormously in a recent years. The increase of research interest in EG penetration into distribution network and placement coordination of several units of EG in distribution system [1]-[4] indicate that the need to understand the impact of connecting an EG into a network has also grown.

The drive for exploring embedded generation in Malaysia is due to its having unlimited renewable energy sources and its pledge to support the Kyoto Protocol. The increase in petroleum oil price also indicates a warning for all so as to seriously considering many other alternatives for energy sources applications. Furthermore, EG placement in a distribution system is not planned beforehand because industries and the IPP, who owns the EG, would rather have an EG installed locally. Domestic EG will also be installed close to home. This way, installed EG might not be strategically placed and thus once installed; it exhibits stability and reliability issues.

The purpose of EG installed at present are to serve as top-up supply and to sell excess MW. This paper will address the relationship of EG control modes with the intention for grid connection. The EG control mode chosen should take into account the purpose of EG connection to the grid.

Studies on generator controls have found that it is possible to equip an EG with flexible mode/s of operation [5]-[6] so that the EG can operate in any mode whenever the network demands it. These control features were intended for voltage regulation and are too complex for SSEG.

Another study [7] utilizes EG which is set at PV mode and conforms to unity power factor while the network loads rely on reactive power supply from external sources. This suggests that connecting such EG to a distribution system will face threats from harmonics.

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A. W. Azizan and V. K. Ramachandaramurthy are with Universiti Tenaga Nasional (UNITEN), Kajang, Selangor, Malaysia (e-mail: azniwati@uniten.edu.my).

C. K. Loo is with Tenaga National Berhad (Distribution) or TNBD, Petaling Jaya, Selangor, Malaysia (e-mail: loock@tnb.com.my).

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Many types of controls for power generations for SSEG are being designed and analyzed [8]-[10]. Some of these control features enable the generators to operate in power factor control mode and voltage control mode. However the focus of analysis was the effect on EG MW penetration level on network losses.

Studies on individual EG placement as in [7] provides some merit to this paper's contents but it concerned minimum system loss on a test system.

This paper focuses on the behavioral characteristics of a selected Malaysian distribution network due to individual influence from a synchronous generator with varied mix of MW and MVAr generations that corresponds to each operation mode. The study is controlled such that the effects of EG mode distribution network profiles can be observed clearly.

The results obtained triggered an appreciation towards the oscillatory behavior of the distribution system when EG is set at PQ control mode. This presentation suggests more simulations and system analysis should be carried out to aid and enhance understanding the behavior of an electrical network when an EG is inserted in the system. The results will assist any IPP who wishes to get its EG interconnected to the utility grid.

III. BACKGROUND RESEARCH

EG in Malaysia operates in power factor control mode. Power factor control refers to a fixed amount of real power and a fixed amount of reactive power generated from an EG. The EG p.f. is set to operate at 0.9 so as not to upset the grid point supply p.f. In this paper, the power factor control mode is referred to as the PQ mode. Whenever the EG real power generation is varied, the reactive power will also be varied at a fixed ratio and at a set p.f. value.

Voltage control refers to the installation of additional equipment, such as the AVR and OLTC transformer, which have to accompany the connection of EG in order to regulate a bus voltage at a specified value. Voltage is regulated by sourcing a fixed amount of real power and a varying amount of reactive power for compensation. Only large generators (>100MW) is equipped with voltage control. In this paper, voltage control mode or PV mode refers to an EG that can source only a fixed amount of real power while the EG terminal voltage is set at a specified value by means of generator excitation system.

The voltage profiles of distribution network vary due to factors such as, the network grid capacity (or the network MVA level), the EG capacity, and the overall loading of a distribution system.

A simulation on a simple 5-bus network shows the effect of EG modes on steady-state voltage at PoC. In the simulation, the grid point supply is represented by an infinite bus, the transformers are identical and of ideal model, and the loads are static loads. For the PQ mode, the EG capacity is increased up to 10MVA at 0.9 lagging p.f. As for PV mode, the real power generation is set according to the EG rating. The relationship between EG modes and EG ratings effect on steady-state bus voltage is plotted on Fig. 1. The comparison indicates that PQ control mode contributes more to the network PoC bus voltage rise and that the voltage rise has a linear relationship with the EG capacity.

This result can be explained by the conventional power flow equation [11] between two bus, which is modified to relate the power flows between EG and the PoC for an active network and is shown in equation (1).

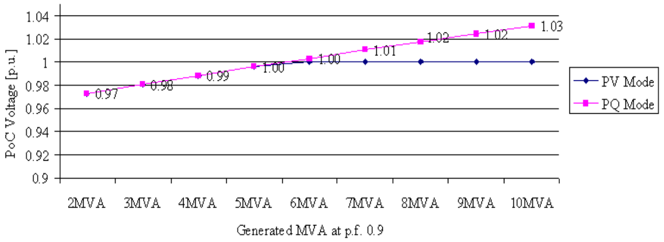

Fig.1 Effect of Generator Modes on Network Steady-state Voltage by Software Simulation

$$\overline{V}_{PoC} = V_{ref} - \frac{RP_{Line} + XQ_{Line}}{V_{ref}} - j\frac{XP_{Line} - RQ_{Line}}{V_{ref}} \tag{1}$$

$$\overline{V}_{PoC} = V_{ref} - \Delta V - j\delta V \tag{2}$$

$\overline{V}_{PoC}$, refers to the voltage at PoC in a network. The general voltage drop equation for ΔV in p.u. is expressed by equation (2) where;

$$\Delta V = \left[\frac{RP_{Line} + XQ_{Line}}{V_{ref}} \right] \tag{3}$$

The parameters at the PoC bus vicinity are defined by Fig. 2. The reference voltage was the value at equilibrium condition prior to EG connection. P_{Line} and Q_{Line} are the resultant powers that flow into the PoC from the grid through the feeder with resistance, R and reactance, X;

P_{Line} = P_Grid + P_EG - P_Load;
Q_{Line} = Q_Grid + Q_EG - Q_Load.

The assumption made for P_{Line} and Q_{Line} is based on the function of EG as a power support to the distribution network power supply. In PV control mode, ΔV is suppressed at zero. In this mode, EG real power generation is constant, therefore EG varies its generation of reactive power into PoC to establish the required voltage at PoC.

Equation (3) indicates voltage rise at PoC if the numerator becomes negative that is, when the power flows from the grid is reversed. It is evident in Fig. 1 that the PoC voltage keeps increasing for PQ control mode as the real and reactive power generation increases in proportion, causing P_{Line} and Q_{Line} to flow in reverse direction from PoC to adjacent bus. When the flows of real and reactive power are negative, voltage difference is positive, thus the PoC voltage rise.

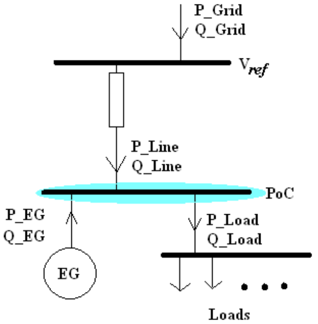

Fig.2 Power Flow Definitions for Steady-state Voltage Drop Calculation

IV. DISTRIBUTION NETWORK TOPOLOGY

A disturbance at an instance of EG connection in the distribution network will display the effect on transient voltage profile. Previous work related to EG generation in PQ mode had shown that when EG power generation increases above a certain value, the EG becomes unstable. PoC voltage profile indicates a continuous oscillation [12]. In this paper, a typical distribution network in Malaysia is selected to demonstrate the effect. The network topology is shown in Fig. 3. The network is modeled in PSCAD/EMTDC software for the subsequent study.

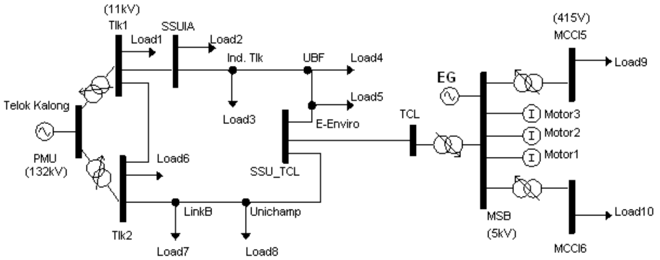

Fig.3 Electrical Distribution Network Topology in Pahang, Malaysia

Table I shows the network line impedances and Table II lists the network components. In this simulation, the feeder lines are assumed to be capable of absorbing the exported power from the EG plant with no overloading problem.

TABLE I
NETWORKS LINE IMPEDANCE FOR THE DISTRIBUTION SYSTEM

Name	From	To	R (ohm/L)	X (ohm/L)	Length (km)
Line1	Tlk1	SSUIA	0.1609	0.1524	2.9
Line3	SSUIA	Ind. Tlk	0.1609	0.1524	0.85
Line4	Ind. Tlk	UBF	0.1609	0.1524	1
Line5	UBF	E-Enviro	0.1609	0.1524	0.55
Line6	E-Enviro	SSU_TCL	0.1609	0.1524	0.574
Line7	Tlk2	LinkB	0.1609	0.1524	1.95
Line8	LinkB	Unichamp	0.1609	0.1524	0.371
Line9	Unichamp	SSU_TCL	0.1609	0.1524	1.75
Line10	SSU_TCL	TCL	0.0745	0.088	0.05

The main substation connected from the transmission grid is represented by an infinite bus that is able to maintain its voltage level at 1 p.u. This is to avoid interference with the transmission network.

TABLE II
NETWORK COMPONENTS LIST FOR THE DISTRIBUTION SYSTEM

Items	Bus Name	Values	
Main Intake	Infinite	132 kV, 60MVA	
Synchronous EG		Round Rotor, 5 kV	Y-Connected, 10 MVA
Transformer 1		30 MVA	132/11kV
Transformer 2		30 MVA	132/11kV
Transformer 3		6 MVA	11/5 kV
Transformer 4		2 MVA	5/0.415 kV
Transformer 5		2 MVA	5/0.415 kV
Motor 1		2 MVA, 300kW	Induction motor
Motor 2		2 MVA, 160kW	Induction motor
Motor 3		2 MVA, 160kW	Induction motor
Load 1	Tlk1	10200 kW, 6320 kVAr	
Load 2	SSUIA	902.7 kW, 559.4 kVAr	
Load 3	Ind. Tlk	255 kW, 158 kVAr	
Load 4	UBF	52.7 kW, 32.7 kVAr	
Load 5	E-Enviro	52.7 kW, 32.7 kVAr	
Load 6	Tlk2	9740 kW, 5882 kVAr	
Load 7	LinkB	42.5 kW, 26.3 kVAr	
Load 8	Unichamp	255 kW, 158 kVAr	
Load 9	MCCI5	493 kW, 303.7 kVAr	
Load 10	MCCI6	493 kW, 303.7 kVAr	

All the transformers are assumed to be able to tolerate reverse power flow. The transformers T1 and T2 are identical and the star winding is on the distribution side.

The EG is a synchronous generator and it is modeled based on the manufacturer's data as shown in Table III. It is set manually to generate power in PV mode and PQ mode. The EG is inserted into the network at 5kV bus after the network converges to its steady-state condition.

TABLE III
THE EG PARAMETERS

Direct Axis Synchronous	X_d	2.08 p.u.
Direct Axis Transient	X'_d	0.355 p.u.
Direct Axis Sub transient	X''_d	0.2343 p.u.
Quadrature Axis Synchronous	X_q	1.892 p.u.
Quadrature Axis Transient	X'_q	0.228 p.u.
Quadrature Axis Sub transient	X''_q	0.2 p.u.
Potier Reactance	X_p	0.163 p.u.
Armature Time Constant	T_a	0.332 sec

The network loads are summarized in Table IV. The static load model selected is constant power model, where this model represents the least severe impact on bus voltage [13].

TABLE IV
LOAD SUMMARY FOR THE DISTRIBUTION SYSTEM

	Static Loads only		**Static Load with motors**	
	Load (MW)	Load (MVAr)	Load (MW)	Load (MVAr)
Calculated	22.487	13.777	23.107	16.148
Measured (PSCAD)	20.448	15.056	20.890	18.850

V. SIMULATION RESULTS

Simulations in PSCAD/EMTDC are performed corresponding to the following conditions:

a) In PV mode, the EG power generations are set at 0.5MW while the PoC voltage is maintained at levels 0.98, 0.97, and 0.96 p.u.
b) In PQ mode, the EG power generations are set at 0.5MW while the p.f. is set at 0.7 leading, 0.9 leading, 0.7 lagging, and 0.9 lagging.

For all simulations, graphs are presented to show the power flowing in/out of PoC and the voltage profiles at PoC corresponding to PQ and PV modes of EG operation.

A. Balanced Power Flows

The power flows obtained provide better comprehension towards the behavior of a distribution network when an EG is connected. Fig. 4 and Fig. 5 demonstrate balanced power flow in and out of PoC for PV and PQ control modes when EG generation is 0.5MW at controlled voltage of 0.98 p.u. and p.f. of 0.9 respectively.

Referring to Fig. 4, the EG is synchronized and connected to the distribution network in PV control mode at Time = 1 second. Applied mechanical torque controls the EG real power generation.

At Time < 1.25 seconds, the EG behaves like an induction generator. Its excitation is supplied by the distribution network voltage at MSB bus. Q_Grid profile in Fig. 4(b) indicates that the EG draws current from the grid in order to build up field flux and create armature reaction.

As the build-up of flux saturates, armature reaction increases the EG speed and develops torque as EG real power increases. During this time, the grid supplies reactive power to the EG, thus the voltage drops at PoC as shown in Fig. 4(c).

The developed torque also overcomes the voltage drop and reaches the set value. At approximately 1.25 seconds EG starts generating reactive power into PoC. The EG speed increases further, exceeding its synchronous speed, and develops counter torque. About 2.5 seconds, EG active power (P_EG) reduces to 0.5MW and stabilizes.

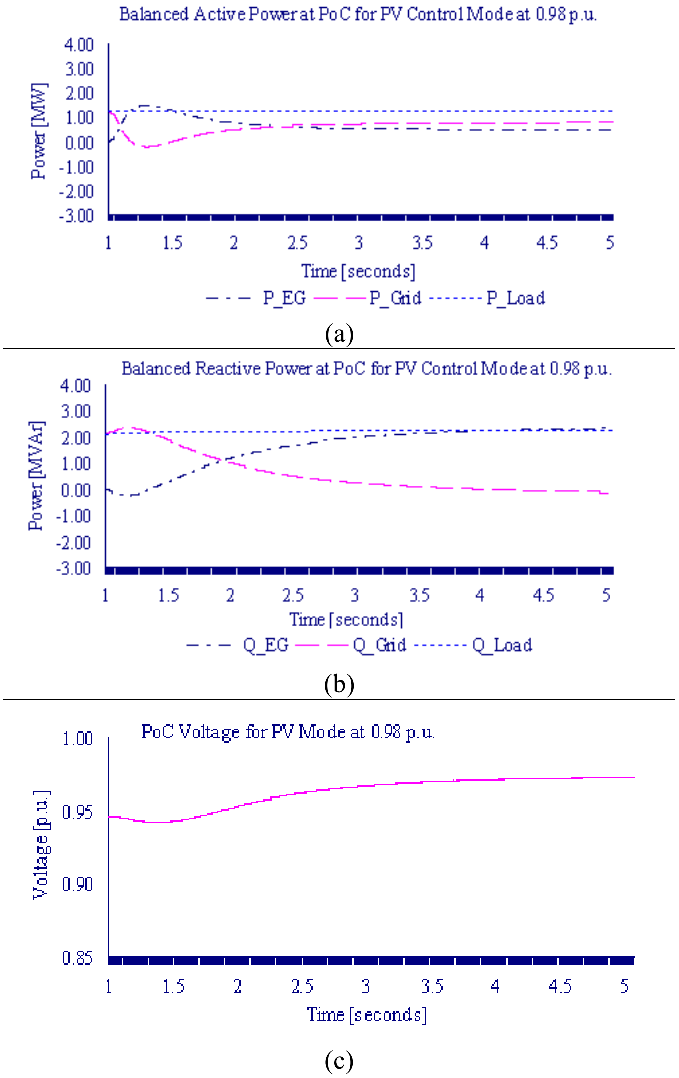

Fig. 4 Balanced Power Flow and Voltage Profile at PoC for PV Control Mode (a) Active Power Flow into PoC (b) Reactive Power Flow From the Grid into PoC (c) Voltage at PoC

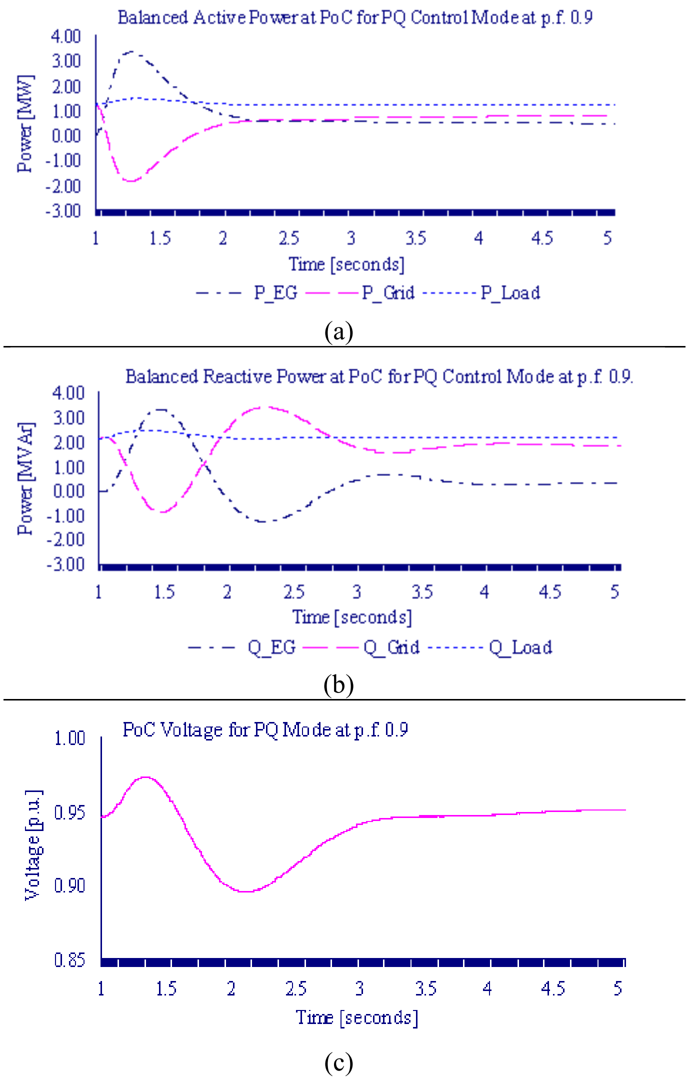

Fig. 5 Balanced Power Flows and Voltage Profiles at PoC for PQ Control Mode (a) Active Power Flows into PoC (b) Reactive Power Flows from the Grid into PoC (c) Voltage at PoC

The reactive power (Q_EG) increases further until voltage at PoC reaches 0.98p.u. As seen in Fig. 4(b), the grid reactive power (Q_Grid) diminishes when this voltage is reached.

In PQ mode, EG generates both active and reactive power into PoC at the instance of grid connection. This is achieved by applying a driving torque and controlling the EG field voltage. With reference to Fig. 5(a), at Time < 1.25 seconds, the applied torque increases to its maximum thus the active power from EG (P_EG) overshoots.

Meanwhile, Fig. 5(b) indicates that the initial field voltage induces high field current, therefore field flux builds up and the EG starts generating reactive power into PoC. Both active and reactive power penetration into the grid result in voltage overshoot at PoC and is shown as Time approaching 1.5 seconds in Fig. 5(c). By this time, counter torque is created causing P_EG to reduce to 0.5MW.

Due to high voltage at PoC, field excitation remains high, resulting in maximum Q_EG flowing into PoC. After Time = 1.5 seconds, counter torque created earlier has increased and reduces the field current, thus reducing field flux build-up. As seen in Fig. 5(b), Q_EG oscillates before it reaches the set value of 0.24MVAr.

The remaining reactive power towards the local load is supplied by Q_Grid so that the sum totals up to Q_Load (2.15MVAr). It is also observed in Fig. 5(c) that the PoC voltage responds in accordance with Q_EG.

At an EG active power generation of 0.5MW, the EG is supporting a portion of the local active load (P_Load) of 1.24MW, while the remaining power demand is supplied by the grid. This is shown by the P_EG and P_Grid profiles at steady-state for both EG power generation modes in Fig. 4(a) and Fig. 5(a).

The EG active and reactive power flow profiles are out of phase with the corresponding grid powers indicating power exchange between the EG and the grid has taken place at PoC.

In PV control mode, the balanced power flow profiles strongly suggests that EG is supporting the network by supplying sufficient reactive power to raise the voltage at PoC to a desired level.

In PQ control mode, EG is supporting the grid in supplying the local load, which indicates that this mode can be utilized when any IPP intends to sell its generation to the grid.

B. Effect of EG Generation Mode Parameter on Grid Power Flow

The following simulation result shows the influence of various PV and PQ parameter settings on the grid power flows into PoC and provides more insight into the power exchange phenomenon. The simulations assume balanced power flows as described in previous paragraphs.

Fig. 6 and Fig. 7 show the results of P_Grid and Q_Grid profiles corresponding to EG power generation in PV control modes at voltage control levels 0.98p.u., 0.97p.u., and 0.96p.u.

The effects of varying the EG power generations at lagging and leading p.f. of 0.7 and 0.9 are presented in Fig. 9 and Fig. 10.

The P_Grid profiles in Fig. 6 are the same since the P_EG generated are subjected to 0.5MW. The sagging portion of the P_Grid trace indicates that the EG active power generation increases at the application of the driving torque. The grid power adjusts to accommodate for the local active power demand.

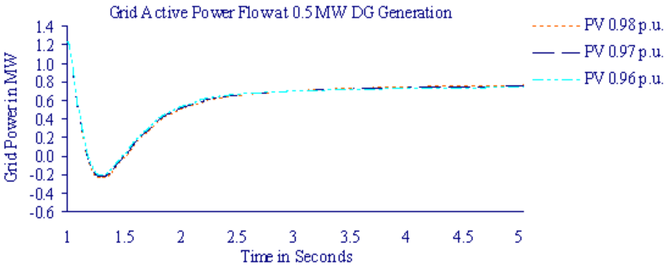

Fig.6 Comparison of Active Power Flow (P_Grid) into PoC for PV Mode Control Levels

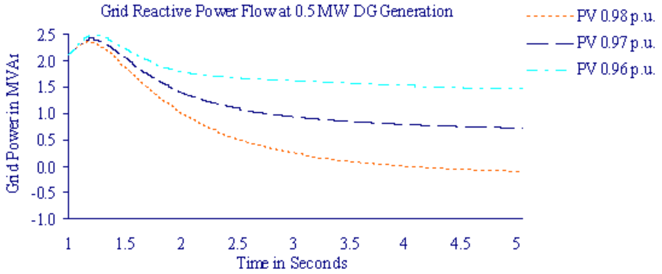

Fig.7 Comparison of Reactive Power Flow (Q_Grid) into PoC for PV Mode Control Levels

With reference to Fig. 7, the Q_Grid profile of PV control at 0.98p.u. indicates insufficient reactive power generated by the EG to maintain the PoC voltage at 0.98p.u. At this setting, Q_EG can only raise the voltage of PoC up to 0.97p.u. as shown in Fig. 8. The amount of Q_EG generated into the grid is about 2.4MVAr. There is excess of about 0.25MVAr reactive power flowing into PoC, resulting in reverse Q_Grid. At other PV control settings, Q_Grid flow allows for EG reactive power generation to support the voltage at PoC.

Fig. 8 shows the resulting voltage at PoC corresponding to each PV mode settings. Profiles for PV 0.98 and PV 0.97 are overlapping, thus explains the limitation of PV control mode as voltage support mode to the network.

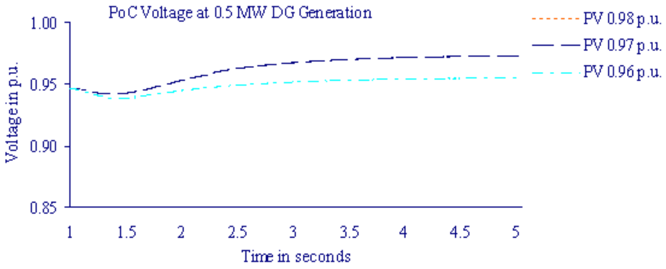

Fig.8 Resultant Voltage Profile at PoC due to PV Mode Control Levels

PQ mode settings have distinctive effect on the transient of grid active power flow as observed in Fig. 9. At lagging p.f. the P_Grid profiles almost overlap, while at leading p.f. the reverse P_Grid at its maximum for PQ p.f. 0.7. The transient dies out at the same time (4 seconds after connection).

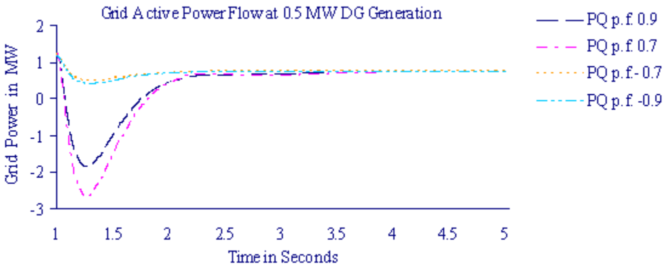

Fig. 9 Comparison of Active Power Flow (P_Grid) into PoC for PQ Mode at Various p.f. Settings

The comparison of Q_Grid profiles in Figure 10 shows that the grid oscillates more when EG is connected at a leading PQ mode. The maximum amplitude of Q_Grid oscillation corresponds to the leading PQ p.f. 0.7 setting.

The reactive power oscillation as in Q_Grid profile introduces voltage oscillation at PoC and the maximum amplitude of oscillation also corresponds to the leading PQ p.f. 0.7 setting. Voltage profiles at PoC for the PQ mode settings can be observed in Fig. 11.

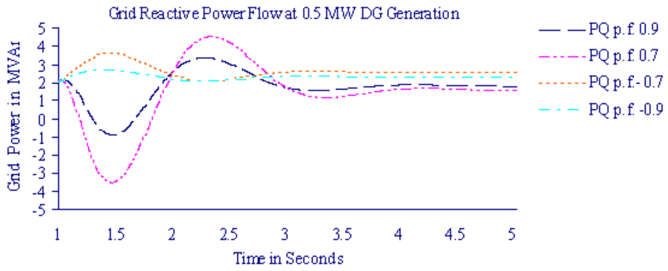

Fig.10 Comparison of Reactive Power Flow (Q_Grid) into PoC for PQ Mode at Various p.f. Settings

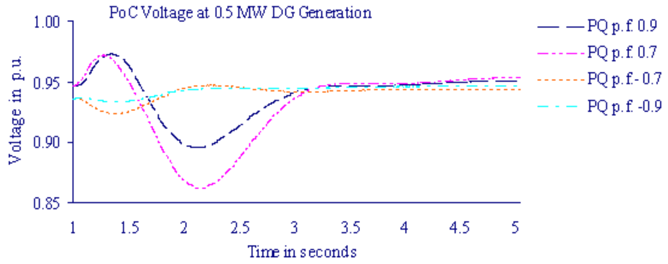

Fig.11 The Resultant Voltage Profile at PoC for PQ Mode at Various p.f. Settings

Factors that influencing the rate of power flow oscillation in an electrical distribution network are the load angle ϕ, the power angle δ, the machine inertia, and the strength of the network. Further research related to these aspects is being carried out.

VI. CONCLUSIONS

Connecting an EG into a distribution network introduces load switching and disturbs the steady-state network operation. The instance causes system to oscillate which results in oscillating power flow. Table V summarizes the effects of inserting EG with PV and PQ control modes into a distribution network.

TABLE V
SUMMARY OF THE GENERATOR CONTROL MODE INFLUENCE ON THE DISTRIBUTION NETWORK PROFILE

PV	PQ
Active power profiles are the same for all settings	Active power profiles vary at different settings
Over damped reactive power flow profile	Oscillating reactive power flow profile
Reactive power change smaller at lower PV control setting	Reactive power amplitude higher at smaller leading p.f. value
Network voltage sags at transient	Network voltage oscillates with maximum amplitude at smaller leading p.f. value

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VIII. BIOGRAPHIES

Azni Wati Azizan received BSc in Electrical Engineering from Worcester Polytechnic Institute of Massachusetts, U.S.A in 1991 and MSc (Microelectronics) from UKM Bangi, Malaysia in 2003. Azni is an IEEE Member and presently pursuing her PhD Degree in Electrical Engineering at UNITEN. She leads two projects which focus on embedded generation issues in power distribution system.

Dr. R. Vigna Kumaran completed his PhD at UMIST, UK in 2001. Dr. Vigna presently heads the Power Quality Research Group in UNITEN. Dr. Vigna also leads several researches and consultancy projects and has authored more than 50 International papers in the areas of power system, power quality and embedded generation.

Ir. Loo Chin Koon received an Electrical Engineering Degree from the University Technology Malaysia in 1987. He started his career with Tenaga Nasional Berhad (TNB) in 1987 and has held various posts in areas of planning & design, operation & maintenance, customer service, and interconnection of embedded generation. Loo completed his postgraduate study in Engineering Management at UNITEN in 2003. He is member of the Institution of Engineers Malaysia (IEM) and holds an Energy Commission competent engineer certificate.