Control Strategies for Gas Turbine Generators for Grid Connected and Islanding Operations

Pukar Mahat, Zhe Chen and Birgitte Bak-Jensen

Abstract— Islanding operation of distribution systems with distributed generations (DG) is becoming a viable option for economical and technical reasons. However, there are various issues to be resolved before it can be a reality. One of the main issues is control of the DG. Control strategies, that may work fine while a DG is connected to a grid, might not work as desired while it is islanded and vise versa. This paper presents a strategy to operate distribution systems with a small gas turbine generator (GTG), which is capable of supplying local loads, in both islanding and grid connected conditions. Separate strategies are used to control the GTG while it is connected to the grid and while it is islanded. Switching between the control strategies is achieved through a state detection algorithm that includes islanding and grid re-connection detections. An existing islanding detection technique has been used and a grid re-connection detection algorithm has been developed. Simulation results show that the proposed method is effective in operating GTG optimally while it is either connected to the grid or islanded.

Index Terms— Droop control, gas turbine generator, grid re-connection detection, islanding detection, isochronous control, power factor control.

I. INTRODUCTION

Traditional distribution systems didn't have any active power generating sources in them. With the renewed interest in distributed generation, this presumption is no longer valid. Penetration of DG in distribution systems around the globe is increasing and current signs show there is no slowing down in near future. Global environmental concerns, liberal energy markets and constraints on right of way have all helped to foster DG technologies. One of the DG technologies that have been popular in Denmark is gas turbine generators. They have become increasingly popular due to their lower greenhouse emission as well as higher efficiency, especially when connected in a combined cycle setup [1]. As a result of significant penetration of DG in many distribution systems worldwide, islanding operation of a part of a distribution network supplied by local DG units has recently attracted global interest [2]. In Denmark, there is a real possibility to operate distribution systems in an islanding mode with small GTGs supplying power to a small area. Even though islanding operation of distribution systems with local generators is a viable option, there are various issues to be resolved. One of the major issues is voltage control of the islanded system.

When a small GTG based on synchronous generator is connected to grid, it can be operated in terminal voltage or VAr/power factor control mode. However, when operated in the voltage control mode, it may cause either over or under excitation of the small generator as it will attempt to maintain the voltage at a set point with its continuously acting terminal voltage regulator [3]. Also, an excessive reactive current may result in overload or loss of generator synchronism [3]. According to [4], small generators' operation at the VAr/power factor control mode is justifiable. Furthermore, it makes economical sense to operate small GTGs at unity power factor. However, when the distribution system is islanded, the voltage might go beyond the power quality limits. In such a case, the GTG has to maintain the distribution system voltage by controlling the reactive power. Another issue that has to be resolved is frequency control of the islanded system.

Many generators use speed droop governor that changes the governor reference speed as loads change. However, depending on the power mismatch on the islanded system, the system frequency may settle well outside the power quality limit as shown in Fig. 1.

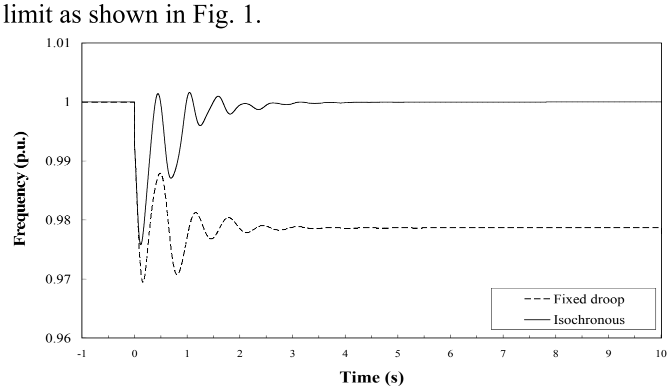

Fig. 1. Frequency of an islanded distribution system.

The problem of frequency settling outside the power quality limit can be solved by an isochronous speed controller that has the ability to bring the GTG speed to the reference speed after islanding as shown in Fig. 1. But the problem with the isochronous controller is that it cannot be used while the GTG is connected to a strong grid. The output of the GTG will be

P. Mahat, Z. Chen and B. Bak-Jensen are with the Institute of Energy Technology, Aalborg University, Pontoppidanstræde 101, Aalborg, DK-9220, Denmark (e-mails: pma@iet.aau.dk, zch@iet.aau.dk, bbj@iet.aau.dk).

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driven to the limit even with the slightest of frequency deviations as shown in Fig. 2. Again, it makes no economical sense to reduce power generation to zero in an attempt to maintain system frequency to nominal while reduction in power production from the small GTG hardly has any impact on system frequency. However, when the system frequency increases, the speed droop controller will increase its speed reference and finds a new operating point as shown in Fig. 2.

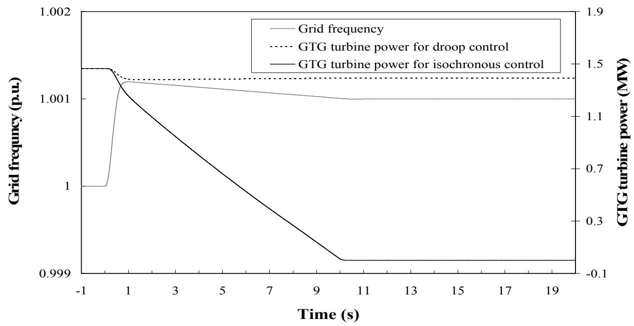

Fig. 2. GTG active power and transmission grid frequency.

Fig. 1 shows that the isochronous controller works better when the system is islanded. Fig. 2 shows that the speed droop controller works better while the system is grid connected.

This paper presents a strategy to operate distribution systems with a small gas turbine generator, which is capable of supplying local loads at any time. It proposes to operate the GTG at a constant or unity power factor with speed droop control while the GTG is connected to grid and to operate with voltage control and isochronous control while the GTG is islanded. The switching between the two control strategies is done through state (grid re-connected or islanding) detection. Islanding can be detected in various ways. Recent developments in islanding detection are reviewed in [5]. Mostly used islanding detection techniques may be classified as active and passive techniques. However, passive methods cannot detect islanding when the load and generation in the islanded system closely match whereas active methods inject unnecessary perturbations in the system. For the purpose of this study, the hybrid islanding detection method described in [6] is used. It combines real power shift (RPS) and average rate of voltage change (ARVC) to efficiently detect islanding. Furthermore, a grid re-connection detection technique has been developed and presented in this paper.

The proposed methodology is presented in Section II. Modeling of GTG is explained in Section III. The proposed method is tested in a radial distribution system, which is presented in Section IV. The test system and controllers are modeled in DigSILENT PowerFactory 13.2.334 and the results are presented in Section V. Section VI concludes the paper.

II. Proposed Methodology

Fig. 3 shows the flow chart to control a small gas turbine generator that has the ability to supply local loads when the distribution system is islanded. While the distribution system is connected to the grid and no islanding is suspected, the GTG will supply power at constant power factor and its power is controlled by a speed droop governor. When islanding is suspected but not confirmed by the ARVC, the RPS is initiated [6] that will increase or decrease the active power reference of the GTG with increasing or decreasing voltage at the GTG bus, respectively. During the RPS, the speed error is kept constant. This will force the turbine to follow the power reference, which means that the RPS will change the GTG power in relation to the amount it was producing before initiation of RPS. If the speed error is not kept constant, then it will counteract the RPS. As a result, the desired change in power, to correctly detect islanding, may not be achieved. When the islanding is confirmed, the GTG will start to operate in the voltage control and isochronous control mode. However, if the detection algorithm shows that the system is not islanded, the RPS is disabled and the GTG continues to operate in power factor control and speed droop control mode. If the system has been islanded and should later be re-connected, synchronization of the distribution system to the transmission system is done through sync-check relay. When the distribution system is re-connected to grid, the GTG will change its power with the slightest of changes in grid frequency to bring the speed back to reference, with the isochronous control. As the transmission grid is stronger than the GTG, change in the GTG speed will be minimal. Hence, grid re-connection is identified when:

- The GTG power (P) is minimum (P_{min}) and speed (ω) is increasing, as there are no other power sources,
- The GTG power is maximum (P_{max}) and speed is decreasing as local loads are always within the capacity of the GTG, and
- The rate of change of speed over power ($d\omega / dP$) of the GTG is less or equal to zero for 10 half voltage cycles as change in power is not having the desired impact on speed. Observing $d\omega / dP$ for 10 half voltage cycles reduces chances of false grid re-connection detection during transient conditions.

III. Modeling of Gas Turbine, Governor and Exciter

The block diagram of the GTG control is shown in Fig. 4. It consists of power factor controller and state detection algorithm in addition to generator, turbine-governor and exciter. Both exciter and governor get additional input signals from state detection algorithm whereas the power factor controller gives input signal only to the exciter.

A gas turbine usually consists of a compressor and a turbine operating under the Brayton cycle [7] consisting of four completely irreversible processes, namely, isentropic compression, isobaric heat addition, isentropic expansion, and isobaric heat rejection. A typical model of a gas turbine in stability studies models load-frequency control, temperature control and acceleration control. These components have been reviewed in [8], [9]. Various gas turbine models have been proposed for stability analysis. Rowen proposed a simplified mathematical model for heavy duty gas turbines in [10]. He extended the model by including inlet guide vanes in [11]. But the control loops for speed and acceleration remained essentially the same. IEEE also presented a model of a gas turbine in [12]. Another model is GAST model [13], which is one of the most commonly used dynamic models [14]. These

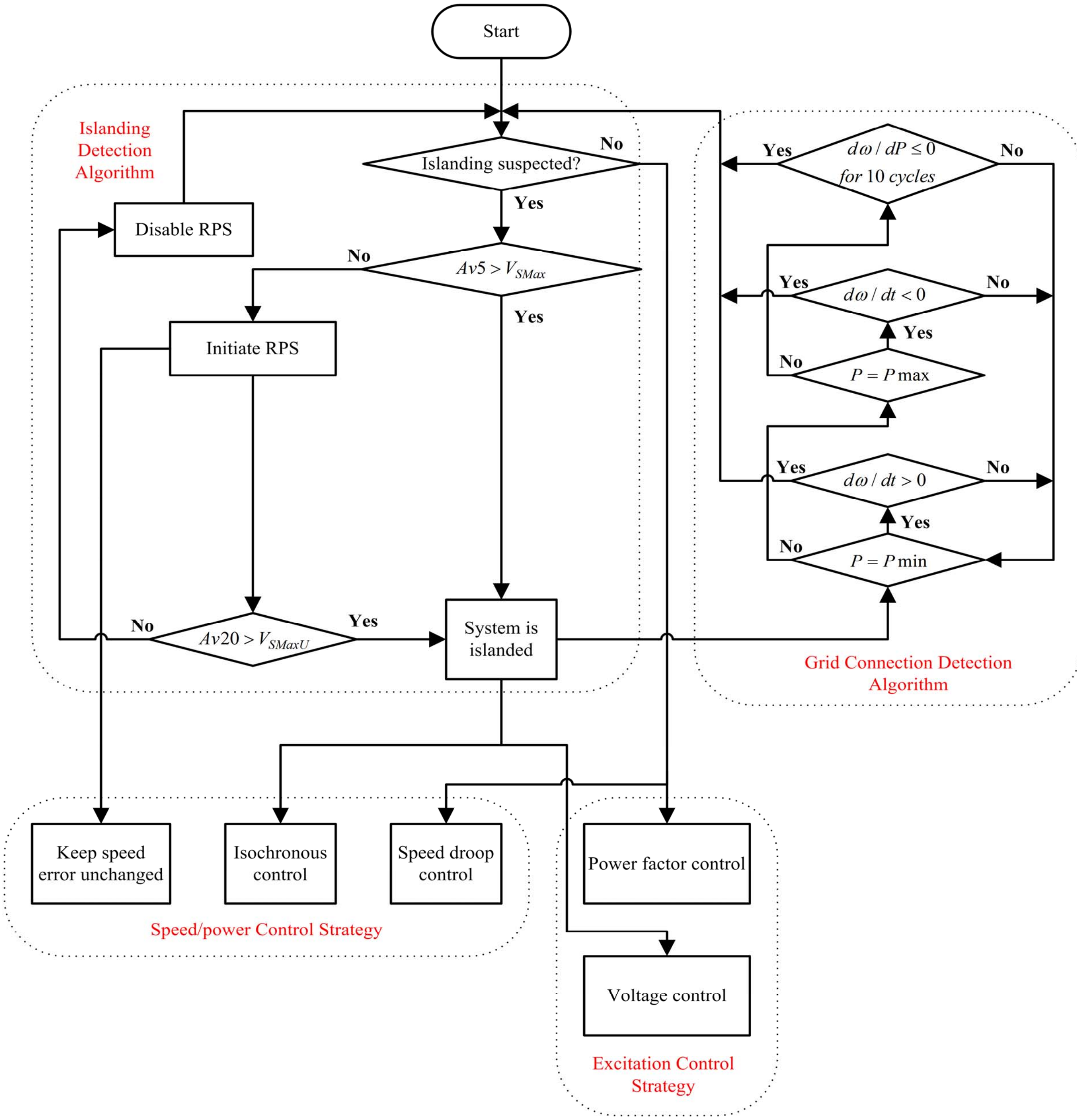

Fig. 3. Flow chart for GTG control.

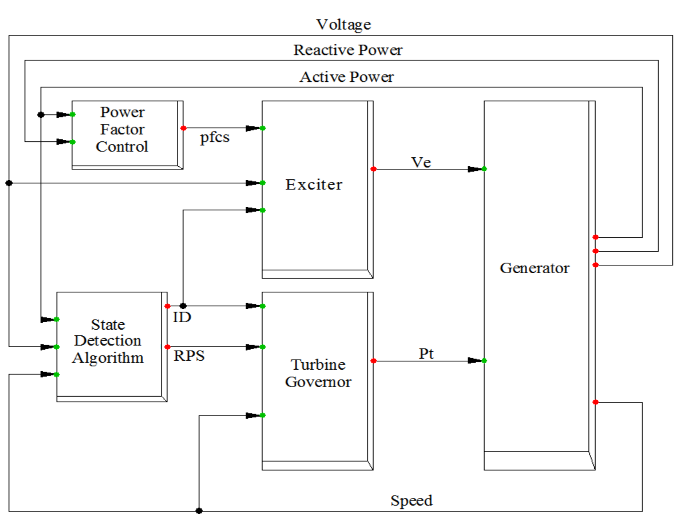

Fig. 4. Block diagram of GTG control.

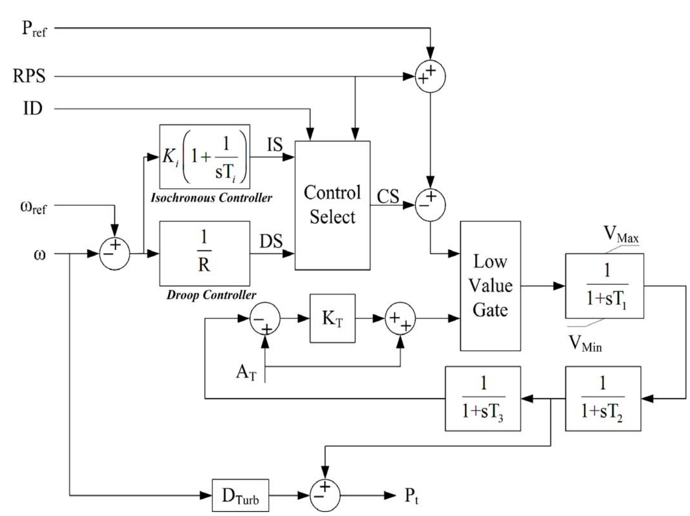

Fig. 5. Modified GAST model.

models and other models are reviewed in details in [15]. For the purpose of this study, it is assumed that the temperature control loop will not become active and hence the GAST model is chosen for its simplicity. The GAST model only employs speed droop governor. Thus, the governor model has to be modified according to the control strategy discussed in Section II.

The modified GAST model is shown in Fig. 5. 'ID' is the islanding detection signal from state detection algorithm and it is '1' when islanding is detected and '0' when the system is connected to grid. 'IS', 'DS' and 'CS' are the control signals from the isochronous controller, droop controller and control select blocks, respectively. P_{ref} is the reference power, K_i and T_i are the isochronous controller's gain and time constant, respectively, R is the speed droop, T_1 is the controller time constant, T_2 is the fuel system time constant, T_3 is the load limiter time constant, A_T is the ambient temperature load limit, K_T is the temperature control loop gain, V_{Min} and V_{Max} are the fuel controller minimum and maximum output, respectively, and D_{Turb} is the frictional losses factor.

IEEE Type AC5A excitation system, which is a simplified model for brushless excitation systems, is used to represent small excitation systems and has been widely implemented by the industries [16]. Hence, for the purpose of this study, this model has been used. However, it regulates the voltage at a fixed point. Thus, an extra signal from the power factor controller is needed to control the power factor. Similarly, ID is required to shift between the control modes. The modified IEEE Type AC5A excitation system is shown in Fig. 6 where 'pfcs' refers to the power factor control signal from the power factor controller. This signal is deactivated when the distribution system is islanded.

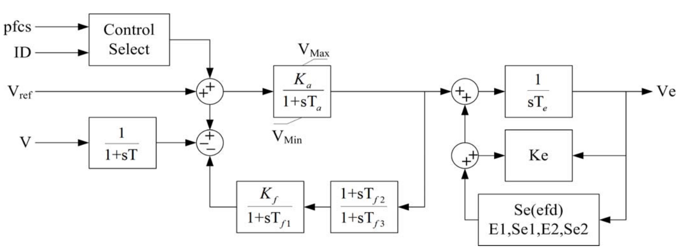

Fig. 6. Modified IEEE type AC5A excitation system.

The power factor controller is shown in Fig. 7. K_{pf} and T_{pf} are the gain and time constant of the power factor controller, respectively.

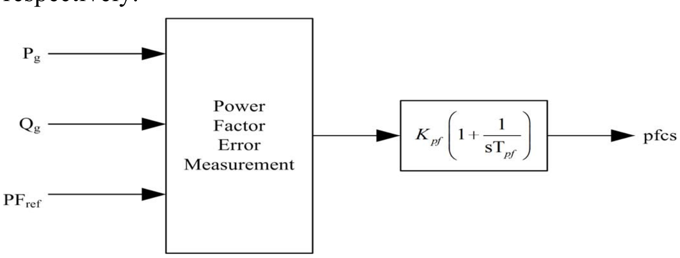

Fig. 7. Power factor control system.

IV. Test System

Fig. 8 shows the model of the test distribution system in which the methodology is tested. The distribution system is a part of a distribution network, owned by Himmerlands Elforsyning, in Aalborg, Denmark. It consists of a GTG and two loads. The distribution system is connected to the transmission network (GRID) at Bus 1 via a circuit breaker (CB) and a transformer (Grid Xmer). The generator data are given in Table AI and the line data are given in Table AII. In the test case, Load 1 and Load 2 are 1 MW and 0.2 MVAr, and 1.51 MW and 0.5 MVAr, respectively. Test case production from the GTG and capacitor bank (CBank) is 2.59 MW and 900 kVAr, respectively. The loads and generations are adjusted to make power mismatch in the distribution system as low as 0.01 MW and 0.01 MVAr. In a real system, loads are always voltage and frequency dependent. However, it is very difficult to determine voltage and frequency dependency of the loads. Hence, for simplicity, loads are modeled as in (1).

$$\left.\begin{aligned} P &= P_0(1+0.5\Delta f+0.5\Delta V) \\ Q &= Q_0(1+0.5\Delta f+0.5\Delta V) \end{aligned}\right\} \quad \textbf{(1)}$$

where, P and P_0 are active load at new voltage and frequency, and base voltage and frequency, respectively;

Q and Q_0 are reactive load at new voltage and frequency, and base voltage and frequency, respectively;

Δf and ΔV are deviations on frequency and voltage in p.u., respectively.

As it is assumed that total load in the system is always within the capacity of the generator, no load shedding is required in the system when it is islanded. Also P_0 and Q_0 are assumed to remain constant during the period of the simulation.

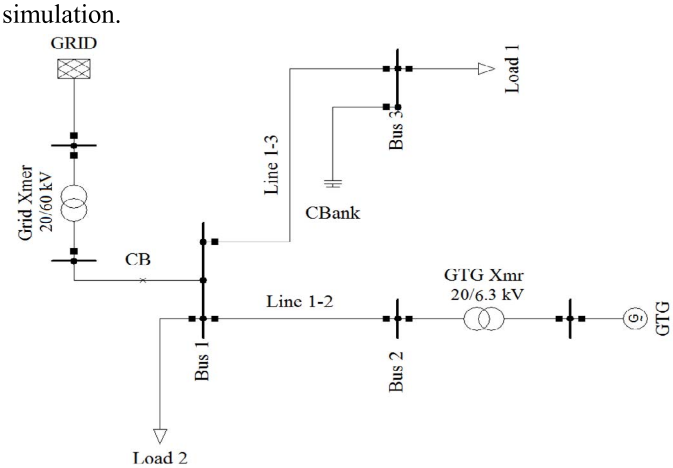

Fig. 8. Test system.

V. Simulation Results and Discussions

The standard model for synchronous generator available in DIgSILENT is used for the study. The parameters for the turbine governor controller and exciter are given in Table AIII and AIV, respectively. Similarly, parameters for the power factor controller are given in Table AV. According to the islanding detection technique described in [6], the minimum set point to suspect islanding (V_{SMin}), the set point to detect islanding without RPS (V_{SMax}) and the set point to detect islanding with RPS (V_{SMaxU}) are set as 10 V/s, 5000 V/s and 100 V/s, respectively. The RPS is set at 2%. The distribution system is islanded at time (t) = 0 seconds (s) by opening the CB. The GTG is controlled at unity power factor while it is connected to grid.

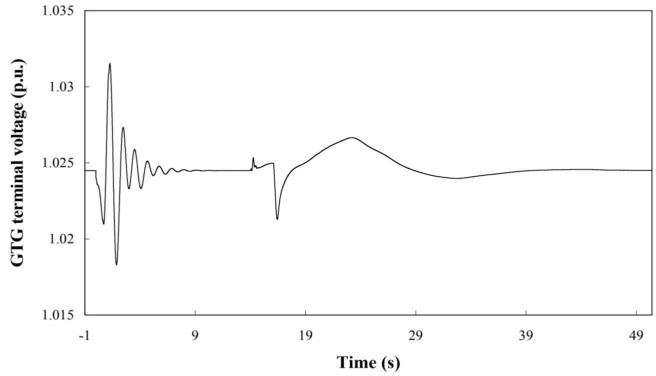

Fig. 9. GTG terminal voltage.

Fig. 9 shows the GTG terminal voltage. When the distribution system is islanded, the GTG terminal voltage goes down and the magnitude of average rate of voltage change for 5 periods ($Av5$) is 178.29 V/s, which is higher than V_{SMin} but not higher than V_{SMax}. Hence, the RPS is initiated at t=0.1 s. Now the magnitude of average rate of voltage change for 20 periods ($Av20$), after initiation of the RPS, is 108.31 V/s, which is higher than V_{SMaxU}. Hence islanding is correctly identified at t=0.5 s.

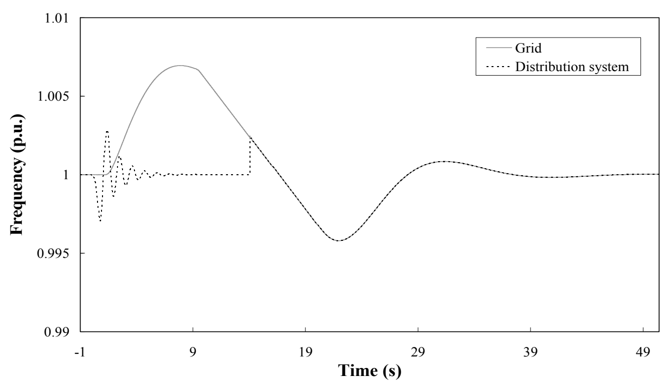

Fig. 10. Transmission and distribution system frequencies.

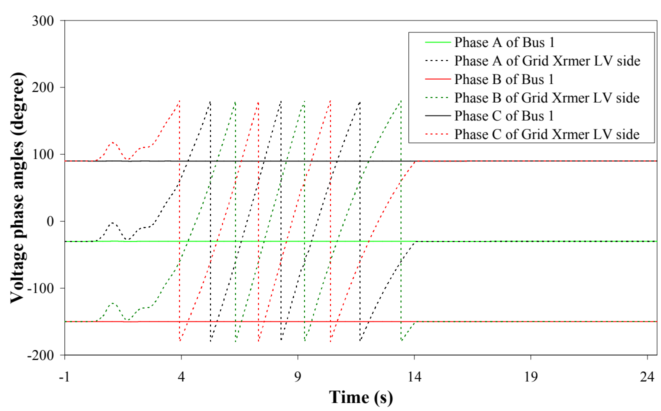

Fig. 11. Bus 1 and grid transformer LV side voltage phase angles.

In a real scenario, grid frequency fluctuates from nominal value. Thus, at some point of time, the distribution system will become in phase with transmission system as the two system do not operate at same frequency all the time. To simulate this, grid frequency is changed as shown in Fig. 10. It also shows the distribution system frequency.

Fig. 11 shows the angles of voltage phases at either sides of CB. At t=13.7839 s, distribution and transmission systems become in phase and they are re-connected.

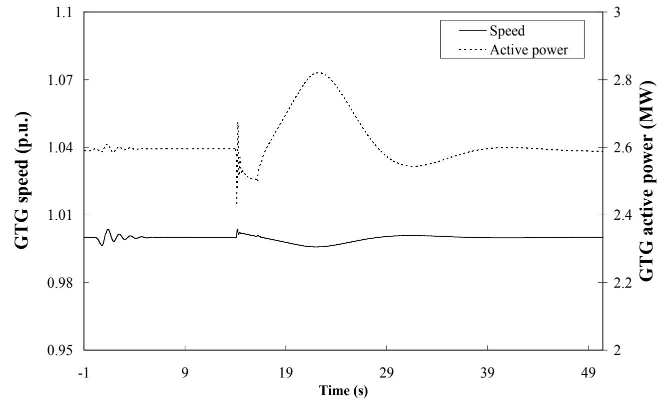

Fig. 12. GTG speed and active power.

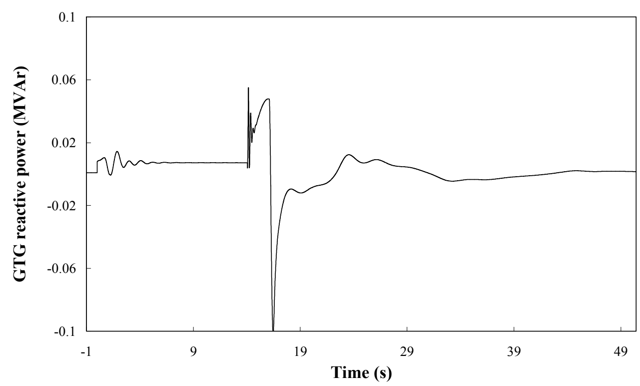

Fig. 13. Reactive power of GTG.

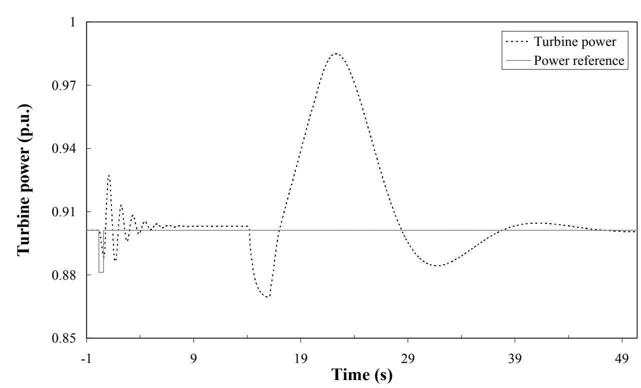

Fig. 14. Reference power and turbine power of GTG.

Fig. 12 shows changes in the GTG active power and its speed. At the time when the distribution system is re-connected to the grid, the grid frequency is going down. Hence, the GTG increases its active power to bring the speed back to reference.

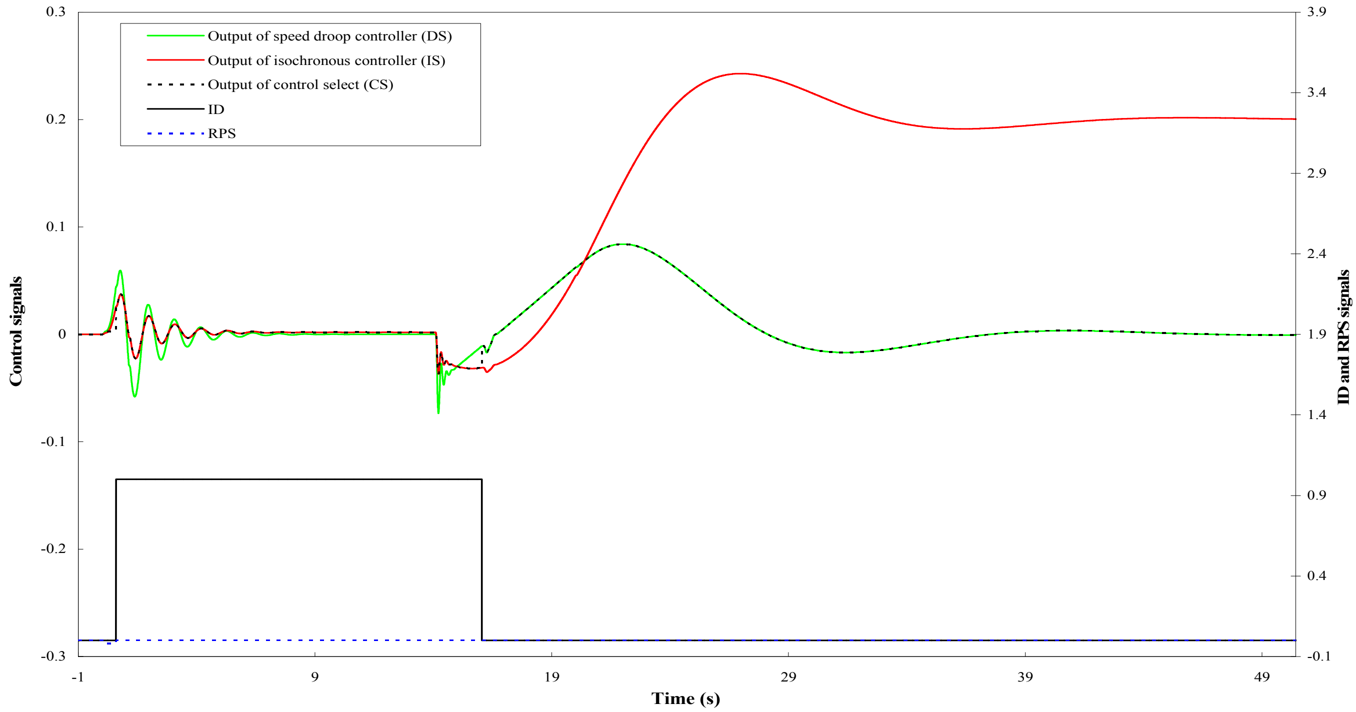

Fig. 15. Controller signals, islanding detection signal, and RPS.

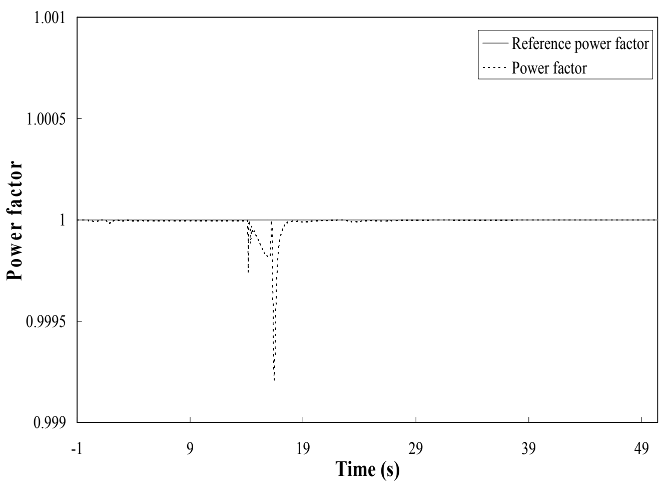

Fig. 16. Reference power factor and GTG power factor.

Since the grid is too strong compared to the GTG, changes in the GTG active power have hardly any impact in system frequency. At t=15.72 s, $d\omega / dP$ becomes zero or less for tenth time and grid re-connection is detected by the state detection algorithm.

Fig. 13 shows the reactive power of the GTG. The reactive power is close to zero while the system is connected to the transmission grid to maintain unity power factor of the GTG. However, reactive power is consumed or supplied to maintain the GTG terminal voltage while the system is islanded.

Fig. 14 shows the turbine power and the reference power. It shows that the power reference is lowered by 2% during the period when the RPS is activated, *i.e.* from t=0.1 s to 0.5 s. The turbine lowers its power as a result. At t=0.5 s, when islanding is detected, the isochronous controller is selected. The turbine increases power as the system frequency goes down. When the distribution system is re-connected to the grid, grid frequency is going down and hence turbine starts to increase power. After the grid re-connection is detected at t=15.72 s, the speed droop control is selected. The turbine power is restored back to reference value when the frequency comes back to nominal.

TABLE I
EVENTS AND CONTROL MODES

Time (s)	Events	Change in Control Mode	
		Yes/No	New Control
-1	Start of simulation	No	-
0	Distribution system islanded	No	-
0.1	Islanding suspected and RPS is initiated as $V_{SMin} < Av5 < V_{SMax}$	Yes	Still in power factor control mode but speed error kept constant
0.5	Islanding detected as $Av20 > V_{SMaxU}$ and RPS is disabled	Yes	Voltage control and isochronous control mode
13.784	Distribution system re-connected back to grid as they are in phase	No	-
15.72	Grid re-connection is detected as $d\omega / dt$ become zero or less for tenth time	Yes	Power factor control and droop control mode

Fig. 15 shows the output of the control select, the droop controller and the isochronous controller, the islanding detection signal, and the RPS. It clearly shows that the control select selects isochronous control when islanding is detected and droop control other time. However, it keeps the speed error constant when RPS is initiated.

Fig. 16 shows the GTG power factor. The power factor controller will provide the signal to control power factor at unity all the time. However, it is only selected when islanding is not detected. It can be seen that the power factor controller will keep the GTG power factor to 1 when the system is not islanded. Table I summarizes all the events and change in control strategies of the GTG during those events.

VI. Conclusions

A technique has been proposed to operate a distribution system with a small gas turbine, which has the potential to supply all the local loads, in grid connected and islanding mode. Also, a technique to determine when the system is re-connected to the grid is proposed.

The GTG operates in different modes when there is a change in states. It operates in power factor control and droop control mode while the system is connected to the grid and in voltage control and isochronous mode while the system is islanded. The shift from grid connected mode to island mode is achieved by detecting islanding whereas the shift from island mode to grid connected mode is achieved by detecting grid re-connection. Simulation results show that the GTG is able to operate optimally all the time. Furthermore, the GTG only uses local resources to detect operating states and local controllers to operate under all conditions. This mitigates the costs associated with a communication infrastructure required for widespread remote control and coordination.

The proposed technique is able to maintain voltage and frequency while the system is islanded and maintain power factor while it is connected to the grid. Furthermore, the GTG is able to find new operating points, while it is connected to the grid, when the grid frequency fluctuates.

Appendix

TABLE AI
GENERATORS DATA

Parameters	Value
Rated power	3.3 MW
Rated voltage	6.3 kV
Stator resistance	0.0504 p.u.
Stator reactance	0.1 p.u.
Synchronous reactance d-axis	1.5 p.u.
Synchronous reactance q-axis	0.75 p.u.
Transient reactance d-axis	0.256 p.u.
Sub-transient reactance d-axis	0.168 p.u.
Sub-transient reactance q-axis	0.184 p.u.
Transient time constant d-axis	0.53 s
Sub-transient time constant d-axis	0.03 s
Sub-transient time constant q-axis	0.03 s
Inertia time constant	0.54 s

TABLE AII
LINE DATA FOR THE TEST SYSTEM

Line	Resistance (Ω)	Reactance (Ω)
1	0.1256	0.1404
2	0.1344	0.0632

TABLE AIII
GOVERNOR SYSTEM DATA

	Parameters	Value
R	Speed droop (p.u.)	0.05
$\mathbf{K_i}$	Isochronous controller gain (p.u.)	10
$\mathbf{T_i}$	Isochronous controller time constant (s)	1
$\mathbf{T_1}$	Controller time constant (s)	0.1
$\mathbf{T_2}$	Fuel system time constant (s)	0.2
$\mathbf{T_3}$	Load limiter time constant (s)	30
$\mathbf{A_T}$	Ambient temperature load limit (p.u.)	1
$\mathbf{K_T}$	Temperature control loop gain (p.u.)	2
$\mathbf{V_{Min}}$	Controller minimum output (p.u.)	0
$\mathbf{V_{Max}}$	Controller maximum output (p.u.)	1
$\mathbf{D_{Turb}}$	Frictional losses factor (p.u.)	0

TABLE AIV
EXCITATION SYSTEM DATA

	Parameters	Value
$\mathbf{T_r}$	Measurement delay (s)	0.
$\mathbf{K_a}$	Controller gain (p.u.)	500
$\mathbf{T_a}$	Controller time constant (s)	0.02
$\mathbf{K_e}$	Exciter constant (p.u.)	1.0
$\mathbf{T_e}$	Exciter time constant (s)	0.9
$\mathbf{K_f}$	Stabilization path gain (p.u.)	0.03
$\mathbf{Tf_1}$	1st stabilization path time constant (s)	0.6
$\mathbf{Tf_2}$	2nd stabilization path time constant (s)	0.38
$\mathbf{Tf_3}$	3rd stabilization path time constant (s)	0.058
$\mathbf{E_1}$	Saturation factor 1 (p.u.)	5.6
$\mathbf{Se_1}$	Saturation factor 2 (p.u.)	0.86
$\mathbf{E_2}$	Saturation factor 3 (p.u.)	4.2
$\mathbf{Se_2}$	Saturation factor 4 (p.u.)	0.5
$\mathbf{V_{min}}$	Controller minimum output (p.u.)	-7.3
$\mathbf{V_{max}}$	Controller maximum output (p.u.)	7.3

TABLE AV
POWER FACTOR CONTROLLER DATA

	Parameters	Value
$\mathbf{K_{FB}}$	Controller gain (p.u.)	50
$\mathbf{T_{FB}}$	Controller time constant (s)	0.5

Acknowledgment

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Pukar Mahat received B.Eng and M.Eng degree from Kathmandu University, Nepal and Asian Institute of Technology, Thailand, respectively.

He was Research Associate at Asian Institute of Technology, Thailand. Since 2007, he has been a PhD candidate at Institute of Energy Technology, Aalborg University, Denmark. Mr. Mahat's research interest includes Distributed Generation, Wind Power Generation and Distribution System Planning. He is a Certified Engineer in Nepal.

Zhe Chen (M'95, SM'98) received the B.Eng. and M.Sc. degrees from Northeast China Institute of Electric Power Engineering, Jilin City, China, and the Ph.D. degree from University of Durham, U.K.

He was a Lecturer and then a Senior Lecturer with De Montfort University, U.K. Since 2002, Dr. Chen has been a Research Professor and is now a Professor with the Institute of Energy Technology, Aalborg University, Denmark. He is the coordinator of Wind Power System Research program at the Institute of Energy Technology, Aalborg University. His research areas are power systems, power electronics and electric machines; and his main current research interests are wind energy and modern power systems. He has more than 170 publications in his technical field. Dr Chen is an Associate Editor (Renewable Energy) of the IEEE Transactions on Power Electronics, Guest Editor of the IEEE Trans. on PE on Special Issue on Power Electronics for Wind Energy Conversion. He is a Member of the Institution of Engineering and Technology (London, U.K.), and a Chartered Engineer in the U.K.

Birgitte Bak-Jensen (M'88) received her M.Sc. degree in Electrical Engineering in 1986 and a Ph.D. degree in "Modeling of High Voltage Components" in 1992, both degrees from Institute of Energy Technology, Aalborg University, Denmark.

From 1986-1988, she was with Electrolux Elmotor A/S, Aalborg, Denmark as an Electrical Design Engineer. She is an Associate Professor in the Institute of Energy Technology, Aalborg University, where she has worked since August 1988. Her fields of interest are modeling and diagnosis of electrical components, power quality and stability in power systems. During the last years, integration of dispersed generation to the network grid has become one of her main fields, where she has participated in many projects concerning wind turbines and their connection to the grid.