Dynamic Phenomena in Wind Farms with a Mix of Line Connected Induction Generators and Inverter Embedded Generators

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***Abstract*-- Power quality and dynamic studies on wind turbines have generally focused on a cluster of induction generators, inverter embedded variable speed generators or other hybrid forms of generation. This paper presents selected results from investigations of the operation of inverter embedded generators and line connected generation together in the form of a microgrid interfaced to a weak electric grid. Simulation results presented in the paper indicate that such an aggregation can be effective in stabilizing the interface and improving baseline power quality levels.**

***Index Terms* — power quality, distributed generation, renewable energy, inverter control, microgrid**

I. INTRODUCTION

Distributed generation systems are rapidly emerging as a dominant alternative to conventional central station based electrical power systems across the world [1]. Among the varied mix of technologies that are emerging, and particularly so among the renewable sources, wind turbine based generation is considered to be the most cost-competitive [2]. They are found in varied applications scenarios such as an island of aggregated hybrid generation systems, a lone turbine connected to a strong utility grid and a farm consisting of a number of turbines including offshore installations [3-5]. Among these scenarios, a lone turbine connected to a strong grid generally poses no particular power quality problem such as voltage flicker, harmonics or stability. An aggregated system consisting of the wind turbine, photovoltaic generation, and diesel generator has to be carefully integrated and operated in order to maintain acceptable power quality levels as has been investigated and discussed in [3]. Multiple wind turbines aggregated together as a wind farm have been known to be susceptible to power quality problems, particularly when interfaced to a weak grid [6]. Most of investigations on this subject indicate a persistence of problems with line connected induction generators and a dramatic improvement of situation with the adoption of variable speed technologies that employ a power electronic converter at the interface coupled to a permanent magnet type or doubly fed induction type of generators [8-10]. The power electronic interface generally provides the possibility for voltage control through reactive current injection, rejection of harmonics through pulse width modulation and vastly improved generation control [11-16]. However, the addition of power electronic converter is an expensive proposition, particularly from the point of power conversion efficiency since it typically adds an additional stage of power conversion. It is the premise of this paper that, in order to reap the benefits of improving the stability of the grid interface and mitigating power quality problems in a wind farm with multiple wind turbines, a hybrid approach can be effective. In such an approach, several conventional line connected induction generators are interfaced to a grid along with a minority of inverter embedded generators. Such a combination is capable of mitigating voltage imbalances at the point of connection caused by load and line imbalances, and providing a stabilizing influence in the neighborhood of the point of connection. Such a cluster of generation devices is often termed a microgrid [17-18]. In the past, studies on microgrids have focused exclusively on interconnected inverter embedded generators such as microturbines. In this paper, the operation of the microgrid in the presence of several line connected induction generators is presented.

The operation of an aggregation of two induction generators interfaced to weak grid is illustrated in Section II as a case study. The case study was chosen particularly to represent a degenerate case that results in sustained oscillations and voltage flicker even under nominal operating conditions. An expansion of the case study with the addition of an inverter embedded generator to form a microgrid and loads is suggested as a mitigating measure. The real power-frequency and reactive power-voltage droop characteristics of

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inverter control that characterize the microgrid are presented in Section III. In Section IV, the inner-loop controls of the inverter to mitigate imbalances and synchronization protocols are discussed. Section V presents selected computer simulation results illustrating the successful operation of the microgrid. Section VI concludes the paper with a brief summary of main concepts presented in the paper.

II. Induction Generators in a Weak Grid

Fig. 1 illustrates the one-line diagram of the case study system under study. The ac voltage V_{ac} with an interconnection impedance r_L and x_L is interfaced to the induction generator IG_L at the local bus B_L., where a local load z_L is connected. Another induction generator IG_L located remotely at B_R is connected to the local bus through a tie line with interconnection impedance r_t and x_t. Both the induction generators have shunt capacitors x_{CL} and x_{CR} connected across them to provide reactive power. A detailed computer simulation of this system was conducted using Matlab Simulink. The line connected induction machines in the simulations incorporated their complete model in the d-q reference frame. Since the dynamic phenomena being studied here are in the order of sub second range, the wind turbine power was modeled a constant with superimposed perturbations representing wind speed and other variations [19-20]. Simulation results from a strong interconnection system and a weak interconnection system are illustrated in Figs. 2 and 3.

It may be observed from the simulation waveforms, when the system interconnection is weak, the source currents and power flow exhibit strong periodic fluctuations caused by the wind speed variations. This would typically result in flicker in the voltage at the load locations both at the local and the remote buses. The dependence of this flicker on the source impedance and its X/R ratio has been studied in the past [21].

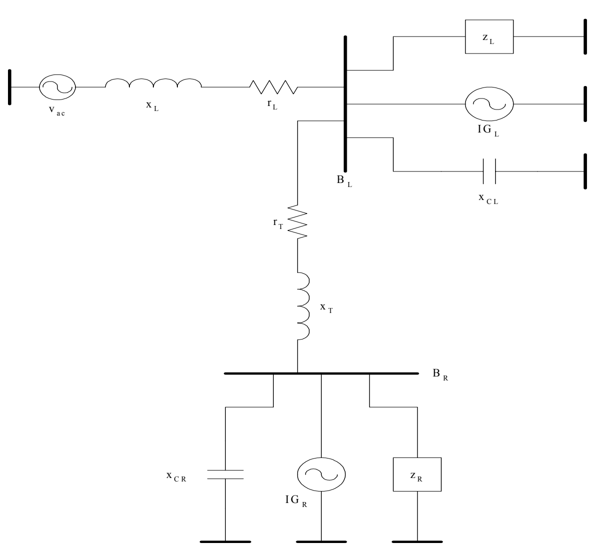

Fig. 1: A one-line diagram of two wind-turbine induction generators connected to a utility grid.

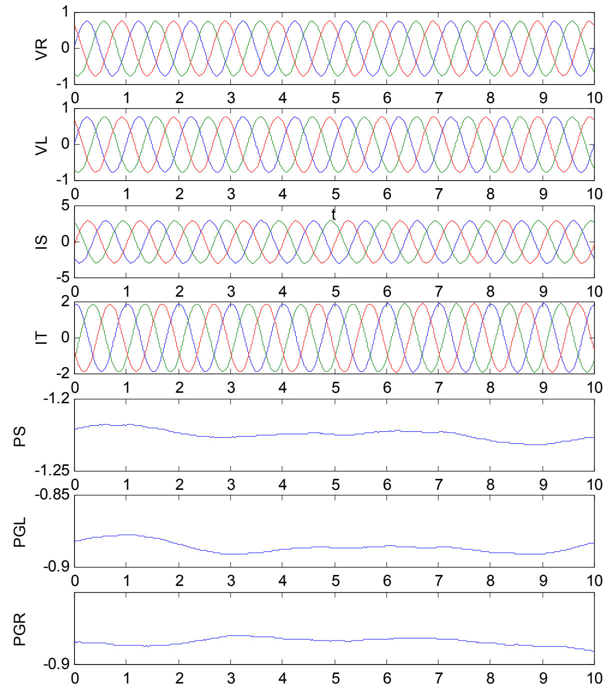

Fig. 2: Waveforms of remote bus voltage (VR), local bus voltage (VL), ac line current (IS), tie line current (IT), line power (PL), local generator power (PGL) and remote generator power (PGR) in per unit quantities operating with a strong interconnection grid with only line connected generators.

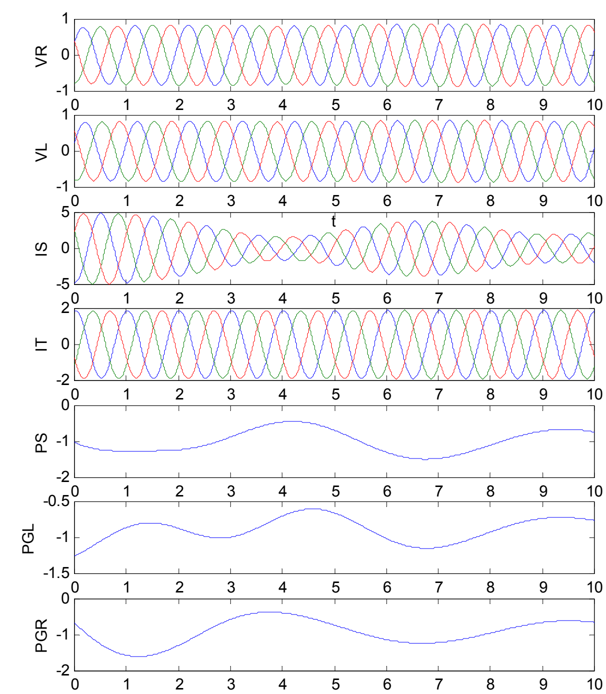

Fig. 3: Waveforms of remote bus voltage (VR), local bus voltage (VL), ac line current (IS), tie line current (IT), line power (PL), local generator power (PGL) and remote generator power (PGR) in per unit quantities operating with a weak interconnection grid with only line connected induction generators.

The application of variable speed wind turbines with inverter interface and the application of static var compensators to reduce flicker and power quality problems have been well known and studied widely. A mix of line connected and inverter embedded generators can be effective in reducing these problems as well. This would be particularly attractive as selective retrofits or selective expansion of the grid can be made to meet load growth. Fig. 4 illustrates the one line diagram of the system, wherein the remote generator has been converted into an inverter embedded generator. The operation and control of the inverter in such a microgrid can be configured to realize various performance advantages as will be described further in the following section.

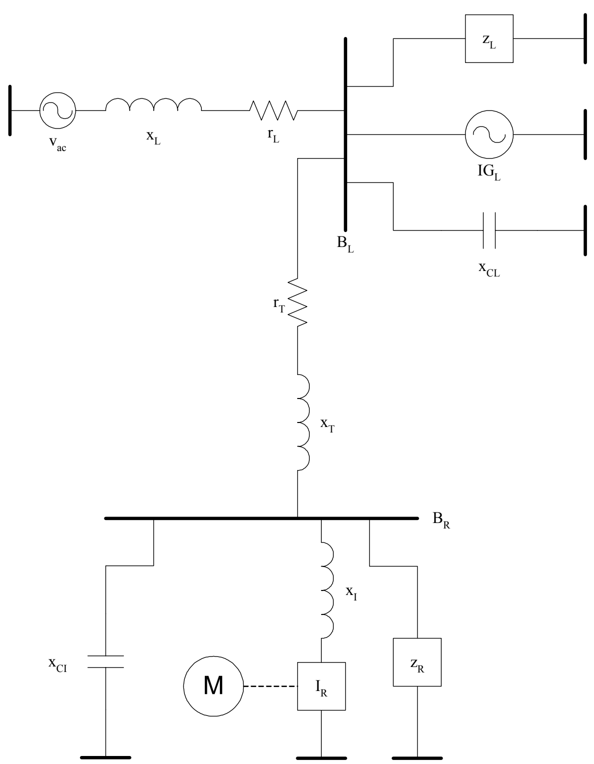

Fig. 4: A one-line diagram of two wind-turbine induction generators connected to a utility grid, with one of them incorporating an inverter interface

III. MICROGRID FEATURES

A microgrid consists of a cluster of small sized three phase ac electrical sources interconnected to meet the energy requirements of loads and perhaps export power to a large utility electric grid. There are three important operational aspects that define a microgrid: (1) the control of voltage and frequency that is distributed among the various generators to ensure stable operation (2) a means of reconnection and disconnection that is autonomous and virtually seamless (3) an appropriate protection strategy for the entire microgrid to ensure electrical safety [18]. Although, the operational strategies for microgrids have been developed and studied widely in recent years, the concepts of system protection are still under development. Hence, the discussion here will be limited to the first two aspects.

The real power-frequency droop and reactive power-voltage droop control of a generator operating in a microgrid are illustrated in Fig. 5. Here, each microsource generator has a reactive power (Q*) and real power (P*) commands that are derived from an outer control device are used to develop the voltage magnitude and instantaneous phase angle commands for the generator.

This control structure enables the tracking of load real and reactive power under islanded mode, when the closed loop regulators are naturally disabled through saturation. Under utility connected operation, the power output of the system follows the command, independent of the load level. Furthermore, under islanded mode of operation with multiple sources, the real and reactive power sharing between different sources are well controlled through the design of regulator gains.

Under grid-connected mode of operation, the power supplied by the microsource is dispatched to be the command value. Any excess power required by the load is drawn from the utility source. However, soon after disconnection from the grid, as illustrated in Fig. 6, the inverter power output immediately rises or drops to follow the load demand.

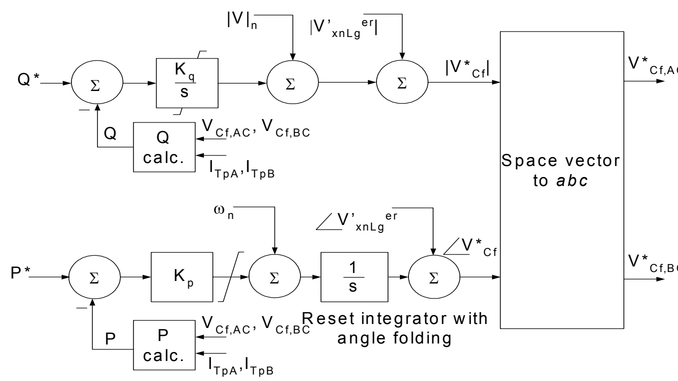

Fig. 5: Block diagram of the external real and reactive power controller for inverter embedded generators in microgrid

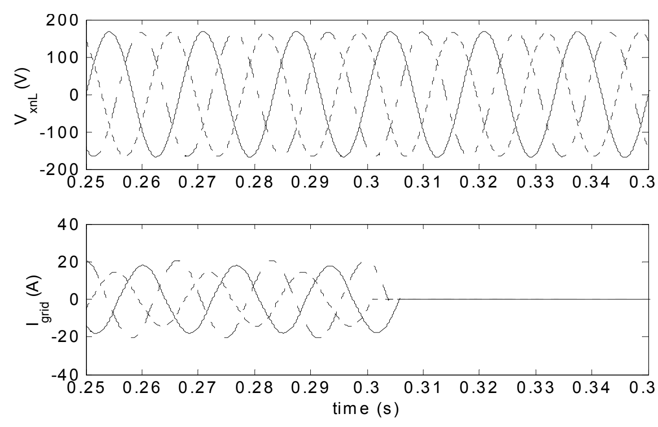

Fig. 6: Three phase voltages (top) and three phase grid currents (bottom) during transition from grid-connection to island mode

Under island mode of operation, the power supplied by the microsource follows the load. Due to the nature of the regulator control loop, the output frequency is not equal to the utility frequency. This results in the three phase systems 'beating' with respect to each other periodically, thereby providing natural opportunities for reconnection. This transient is illustrated in Fig. 7.

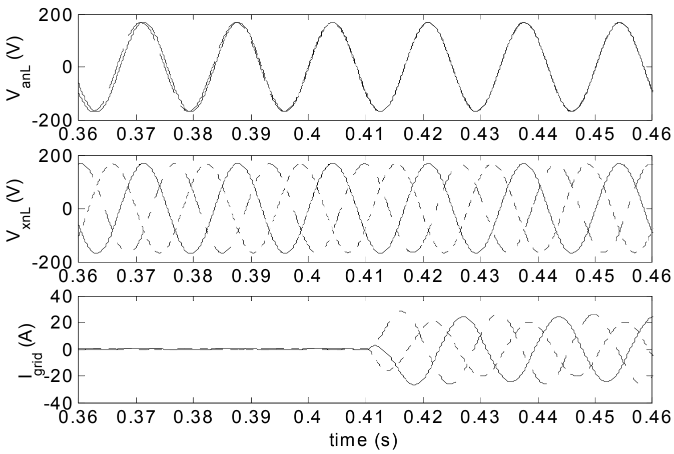

Fig. 7: One phase voltage (top), three phase voltages (middle) and three phase grid currents (bottom) during transition from island mode to grid-connection mode.

IV. Inverter Internal Controls

In addition to the outer loop controls to enable ease of dispatch, inverter internal controls can also be designed to tap into various performance potential provided by the inverter embedded generation approach. Fig. 8 illustrates the schematic of the power circuit of a typical inverter embedded generator. Fig. 9 illustrates the block diagram of an inverter internal control algorithm that is capable of mitigating system and load imbalances. This controller represents a departure from the more common synchronously rotating reference frame based inverter controllers that are drawn from Park's transformation.

The controller illustrated in Fig. 9 has two specific features that make it an ideal candidate for embedded inverters in a microgrid. Firstly, the controller utilizes a complex pole regulator that enables it to have zero steady state error between the three phase inputs and the three phase outputs at a known constant frequency operation as in a utility system. Secondly, the inner current loop and outer voltage loop based hierarchal architecture with load current feed-forward provides excellent transient response. A discussion of design aspects of this regulation system is beyond the scope of this paper and may be found in [22].

Computer simulation results that illustrate the operation of the inverter internal controls under load imbalances are illustrated in Fig. 10. Fig. 11 shows simulation waveforms that demonstrate the operation of the controller under line imbalances. Line imbalances may result from distant faults that cause voltage sags in particular phases. The three wire system of the inverter and the presence of star-delta transformers in the distribution network ensure that the imbalances are limited to negative sequence type. The successful mitigation of these type of imbalances and the transient response of the system are readily evident from the simulation results. This controller has also been shown to compensate for load current harmonics as may be present in the case of nonlinear loads connected to the system [22].

The inner current loop of the regulator also provides an ideal opportunity for controlling the inverter current during faulted modes of operation since the load current and inverter current information is readily available in the control algorithm, typically implemented using a digital signal processing system.

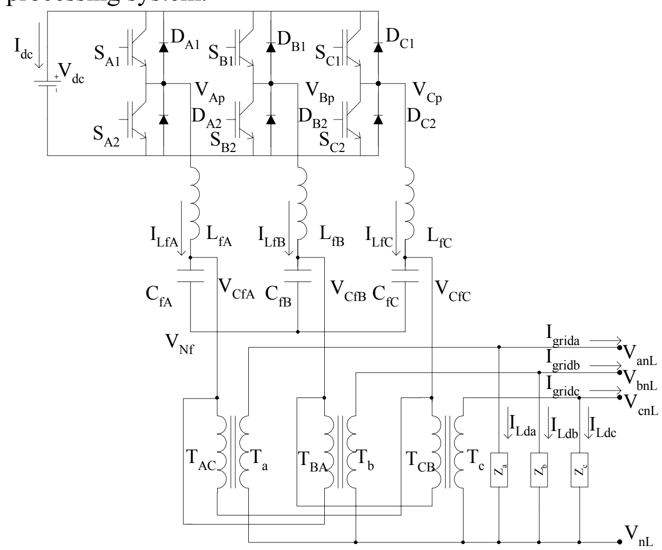

Fig. 8: Schematic of a typical inverter embedded generator interfaced to loads and the utility through a transformer.

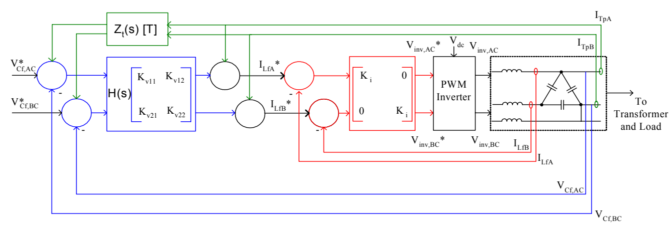

Fig. 9: Block diagram of the controller for regulating the capacitor voltage and inductor current

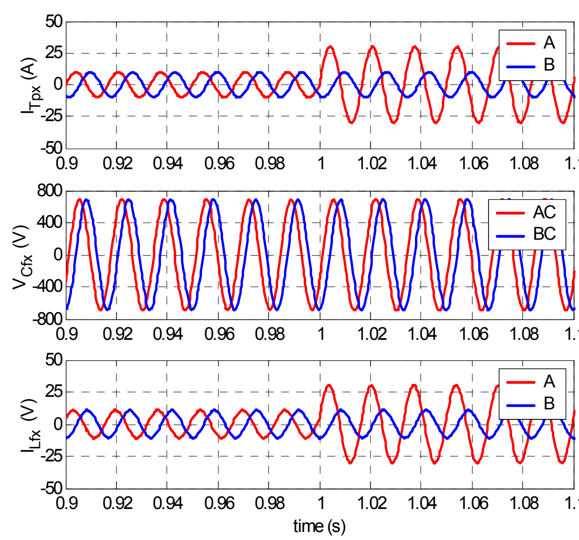

Fig. 10: Load current waveforms (top), load voltage waveforms (middle) and internal filter inductor current waveforms illustrating the system response to negative sequence load imbalance in the island mode of an inverter embedded generator

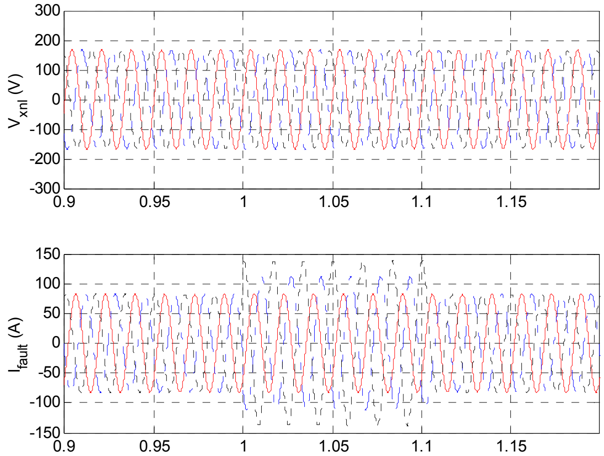

Fig. 11: Load voltage waveforms (top), and fault current waveforms illustrating the system response to a double line-line fault while in grid-connected mode illustrating imbalanced sag mitigation.

V. Induction Generators in the Microgrid

The case study system illustrated in Fig. 4 with a mix of line connected induction generator and inverter embedded induction generator was investigated further using computer simulation. In this case, the external power command of the inverter embedded generator was chosen to follow the power available from the wind turbine thus replicating the conditions of simulations illustrated in Figures. 2 and 3. Corresponding waveforms of the system from the simulation under a strong interconnection to the grid are illustrated in Fig. 12.

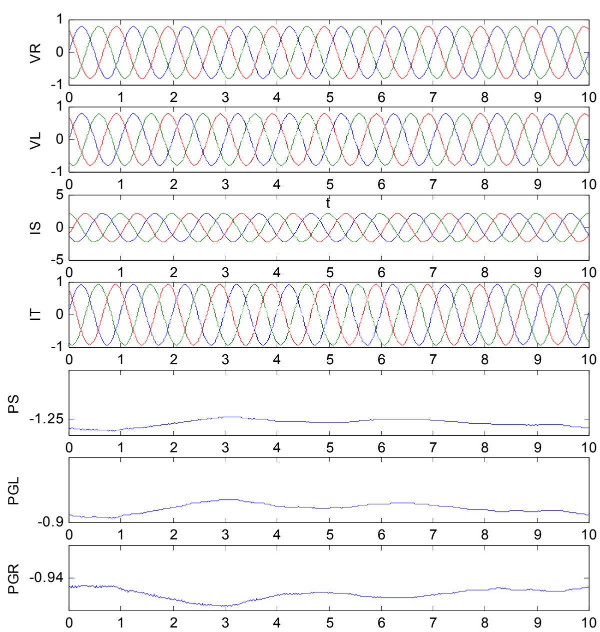

Fig. 12: Waveforms of remote bus voltage (VR), local bus voltage (VL), ac line current (IS), tie line current (IT), line power (PL), local generator power (PGL) and remote generator power (PGR) in per unit quantities operating with a strong interconnection grid with line connected induction generator and inverter embedded generator.

Fig. 13 illustrates the system response under a weak interconnection to the grid. The traces from Fig. 13 may be compared with those from Fig. 3. The improved response of the system is readily evident from the figures. Extensive simulation results indicate similar behavior under various operating conditions including start-up, disconnection and synchronized reconnection transients, and are not included here for the sake of brevity.

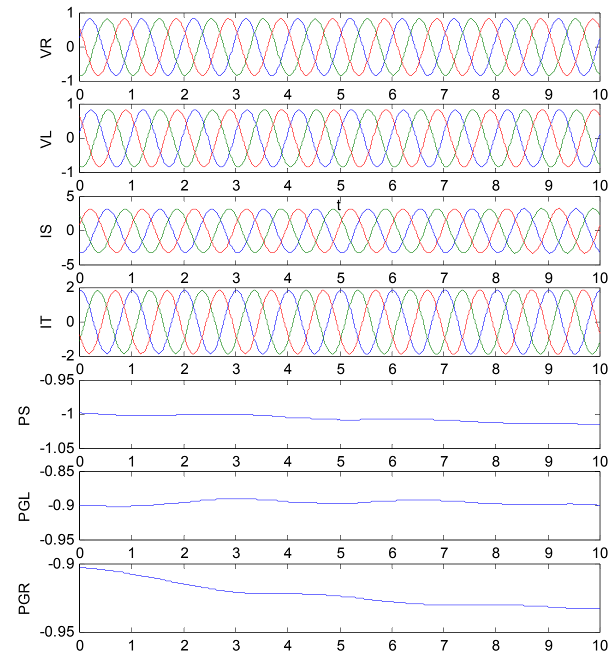

Fig. 13: Waveforms of remote bus voltage (VR), local bus voltage (VL), ac line current (IS), tie line current (IT), line power (PL), local generator power (PGL) and remote generator power (PGR) in per unit quantities operating with a weak interconnection grid with line connected induction generator and inverter embedded generator.

VI. Conclusions

Power quality in wind parks and wind farms with multiple line connected induction generators connected to a weak grid has long been identified to be problematic. In the past in order to improve the interconnection, the use of inverter embedded variable speed wind turbines instead of line connected induction generators have been shown to be highly effective under such conditions. However, this is an expensive proposition. In this paper, a hybrid approach that uses a mix of line connected induction generators and inverter embedded generators have been studied under such conditions and shown to be effective in stable operation of the interconnection in the form a microgrid. Such inverter embedded generators are capable of mitigating typical power quality problems common to problematic interconnections through the application of appropriate internal controls. Extensive simulation results illustrating these concepts have been presented in the paper. Experimental investigations on the microgrid are underway and the results will be reported in the future.

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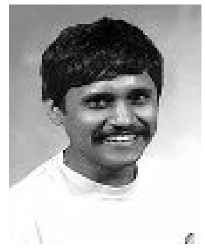
VIII. BIOGRAPHIES



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