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Localized Aggregation of Diverse Energy Sources for Rural Electrification using Microgrids

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Abstract

Extension of electrical service to large rural populations in developing nations is among a key enabling requirement to realize human development goals set forth by international agencies. This paper presents the case for distributed generation in the form of microgrids, which should be the preferred path towards rural electrification in developing communities and a vital complement to expensive centralized grid expansion. The technical features of frequency and voltage control for distributed generation devices in a microgrid are discussed along with a presentation of their stability attributes. Computer simulation results and experimental results from a laboratory scale microgrid are also presented.

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Introduction

Distributed generation (DG) is used here to mean utilization of small generators (<500 kW) that are located in the distribution system or on customer sites to supply electricity directly to end-users, typically in low voltage (<600V) networks. Integration of various DG technologies with the utility power grid is an important pathway to a clean, reliable, secure and efficient energy system for developed economies with established levels of quality and reliability of electrical service (US-DOE 2000). Various studies have found that a good number of utilities as well as consumers that have installed DGs at their facilities realize benefits like local waste heat capture, improved reliability and reduced cost (Willis and Scott 2000, Poore et. al. 2002, ORNL-DOE 2002, Daley and Siciliano 2003). Some authors have called for a fundamental philosophical shift in power system organization (Lovins *et. al.* 2002). Concomitantly, the application of DG in developing economies with relatively spotty levels of electrical service is now also receiving considerable attention (World Bank 1998, World Bank 2004a). Most discussion found in the literature focuses on operation of individual DG systems interconnected to the low voltage network, while some (Tran-Quoc, *et. al.* 2003, Saint and Friedman 2002, Smallwood, 2002) identify the operational issues of DG coordinated in a *microgrid* and embedded in the distribution system, and one author (Alibhai, 2004) presents a complex control option for coordinating a microgrid. One notable microgrid demonstration project has been deployed in Uganda (Brandt 2005). It may be safely stated that technical issues related to controlling individual generators and operating a microgrid are far from definitively resolved. Major issues include frequency and voltage regulation; load tracking and dispatch; protection and safety; and metering and account settlement to match actual energy flows. Among these problems, foremost from an electrical engineering perspective is the local regulation of frequency and voltage in real time, which if not technically feasible renders the very microgrid idea moot. Ensuring frequency and voltage regulation of diverse energy sources is challenging due to their variability of dynamic capabilities, which provides the focal point of this paper.

First, it is argued that aggregation of diverse DG sources in microgrids can be a preferable means of bringing electrification to rural communities in developing nations. Second, a simple DG frequency and voltage control strategy is shown to be capable of ensuring stable microgrid operation, enabling additional layers of operational detail, including protection, safety, metering etc., to be overlaid. Computer simulation and laboratory scale experimental results are presented to verify the successful potential operation of the control principle. The following section contains a discussion of electrical power generation from centralized sources and diverse sources in the socio-economic context of rural electrification. In the next section, operational and technical features of generators in a microgrid are briefly reviewed. Then, a dynamic model illustrating the stability properties of the microgrid, which is followed by concluding remarks.

Context of a Rural Microgrid

In order to address the needs of the world’s poorest citizens, the United Nations (UN) has identified the following eight Millennium Development Goals (MDGs) to be met by the year 2015 (UN 2005):

- Eradicate extreme poverty and hunger
- Achieve universal primary education
- Promote gender equality and empower women
- Reduce child mortality

- Improve maternal health
- Combat HIV/AIDS, malaria, and other diseases
- Ensure environmental sustainability
- Develop a global partnership for development

While the immediate objective of the MDGs is to provide the neediest in poverty-stricken areas with a measure of dignity and hope, the ultimate expected impact is that such an investment strategy will provide the foundation foundations for viable economic growth.

Regardless of the prioritization of the MDGs, any serious effort must focus on strengthening the infrastructure networks of developing countries. Sound infrastructure is crucial to delivery of even the most basic social services and to stimulation of economic activity. For example, transportation links enable children to attend school, the sick to visit clinics, and entrepreneurs to engage in trade. Similarly, communication links enable ready access to information, which can be also used to improve education, healthcare, and trade. Access to electricity has been found to be a key enabling factor in realizing development goals across the board (Saghir 2005). While efforts have been made to improve access to electricity in urban areas of developing countries, viz., through deregulation to increase incentives for private provision of generation (World Bank 2004a), electrical service in rural areas remains largely inadequate. Of the nearly two billion people worldwide without service, nearly 80% live in the poor countries of South Asia and sub-Saharan Africa (IEA 2002).

With no access to electricity, people in these areas resort to energy sources such as kerosene or traditional fuels like wood, crop residue, and animal waste, all of which can cause either deforestation or pollution (WEC 1999). Indoor air quality can be particularly hazardous to women and children where traditional fuels are used (Smith 2006). Besides these direct costs, traditional energy sources also require significant labor, e.g., in collecting the fuels, which could be spent more productively on educational or commercial endeavors. In spite of these severe costs, citizens of poor rural areas have little choice but to meet their most basic energy needs in this environmentally unsustainable and unhealthful manner, as there is insufficient political motivation or capital for costly electrification of affected regions.

The dominant technologies for large-scale centralized grid electrification are based on extraction of energy from fossil fuels, nuclear and hydro at vast scales. While growth prospects for investment in conventional fossil fuel plants are plagued by uncertainties in political and regulatory structures, the environmental viability of large-scale hydropower is coming under increasing criticism (Seshadri 1991, McDonald 1993, Jhaveri 1998). On the other hand, transfer of nuclear technologies for electric power generation is strictly scrutinized and limited due to concerns regarding proliferation and safety (OECD/IEA 2002). Thus, broad development of centralized grid electrification as a preferred approach towards realizing the MDGs will continue to be a troublesome proposition.

Furthermore, financial investment in electrification will tend to favor extension of service territories where they would tend to bring benefit to the people already relatively privileged. This would mean an immediate focus on urban and peri-urban areas where the energy needs are most severe. The cost of developing transmission and distribution networks to rural areas with large distances and low densities appears uneconomic, even with heavily subsidized financing schemes (World Bank 2005).

The meager efforts to expand the traditional centralized grid to rural areas are inadequate to keep pace with population and load growth. For example, one million new rural Indian households are connected to the electricity grid each year, substantially less than the annual 1.85 million households added (World Bank 2004b). Furthermore, the connections that are made are often prone to blackouts. In Rajasthan villages, for instance, outages lasted up to twenty hours per day and occurred on as many as twenty days per month in the 1990s (Chaurey, Ranganathan, and Mohanty 2004).

From the viewpoint of economies of scale, central station power plants enjoy higher fuel to electricity conversion efficiencies than small-scale units at the point of generation; however, the losses associated with energy conversion and transmitting the generated electricity to end-users significantly lower the overall efficiency of the centralized grid. In fact, even in an industrialized country such as the US, transmission losses and waste heat account for most primary energy consumption for power generation (see Fig. 1). Studies of grid operations in developing countries produce similar results.

The size of investment necessary for electrification schemes commensurate with the size of rural communities suggests adoption of cofinancing and microfinancing models that are attractive to third-party agencies interested in entering the market on a build-own-operate, build-transfer-operate or build-operate-transfer modes of development mechanism (Vimmerstedt 1998). Indeed, DG-based efforts are not only flexible enough to reach the most deprived areas at reasonable cost, but also involve the local populace in management of the electrification program, allowing the project to be more customized to local needs than a top-down, centrally imposed paradigm.

In summary, from a socio-economic perspective, the potential exists for DG to offer a preferred expansion path to rural electrification of developing countries. The viability of any particular energy source for development in a community largely depends on local conditions. Indeed, for many isolated rural communities, opting for DG-based microgrids is preferred not only to the *status quo* of relying on traditional fuel sources, but also to the expansion of the centralized network, which has high capital costs and may offer lower effective reliability than dispersed DG.

Technologically, there is substantial evidence of the robustness of DG in serving rural electrification programs. Renewable DG technologies such as micro hydro, photovoltaic cells and small-scale wind turbines are well developed and have been deployed widely in the developing world (World Bank 2002, Davies 1995, Duke *et. al.* 2002). Nevertheless, DG units that run on fossil fuels, such as diesel and natural gas, can be more cost effective than most renewable sources and also benefit from maintenance expertise that is widely available (Petrie *et. al.* 2002). Technologies and operational models for conventional combustion engine generators based on renewable fuels like biomass, bio-diesel, and agricultural waste are also becoming viable through various demonstration projects (Walt, 2004). Furthermore, small hybrid systems based on operating diesel engine generators together with solar and/or wind power systems have been put to use extensively in residential off-grid applications (Senjyu 2002).

Residential scale hybrid systems with multiple forms of generation have often been dc and relied on the presence of a battery bank as energy storage. They tend to be custom designed, focusing on a single residential location and do not allow for easy expansion to meet load growth. The energy storage device allows for leveling variations in power generation and load demand by absorbing excess generation or meeting excess demand as necessary. While the presence of dc storage allows diverse sources to be aggregated, such systems require considerable engineering design effort, and usually require an inverter to develop ac output from the dc storage so that standard mass produced household appliances such as refrigerators, radios and computers may be readily used.

Scaling this dc aggregated approach to design and operate village-scale and community-scale projects constitutes a formidable task due to the technical difficulties of managing power flow and ensuring safety in a low voltage dc network that may span multiple locations. On the other hand, the centralized electric grid as an established model for aggregation of diverse sources provides an inspiration for interconnection and operation of multiple but small electrical sources and sinks. Luckily, the large-scale legacy model itself provides an operational paradigm that can be extended and adapted to facilitate autonomous operation without need for additional infrastructure for dispatch, protection, etc. Any need for such specialized infrastructure would preclude microgrid adoption due to capital and operational costs, and sheer complexity. Such a semi-autonomous ac interconnection of decentralized electricity loads, small-scale (less than 500 kW) generation sources, and storage devices that may or may not be connected to the wider centralized grid (Siddiqui *et. al.* 2002a, 2002b, Lasseter and Piagi, 2000, Venkataramanan and Illindala 2002) is formally herein termed a microgrid.

Generation Control of DGs in Microgrid

A simplified one-line diagram of a microgrid is illustrated in Fig. 2. This schematic does not illustrate the actual wiring, switchgear, protection, etc. At power levels beyond a few tens of kW at multiple load locations, or involving diverse generation, the generation interconnections are more likely to be three phase; however, a majority of the loads are likely to be single phase, consisting primarily of lighting and appliances. While some generators in the microgrid may use rotating machine prime movers, others may employ a dc-ac inverter to derive utility grade power (Illindala *et. al.* 2003).

Planning a control framework for a mixed microgrid comprising of conventional synchronous alternators and a diverse set of inverter-based DG like wind turbines, photovoltaics etc. poses various design and operational challenges because of the dominant practice of having a unique control strategy for rotating machines and power electronics associated with each generator type. For instance, wind turbines traditionally employ a control technique that evolved from motor drives, while photovoltaic converters conventionally use fixed frequency impedance based control strategies reminiscent of spacecraft power systems. Furthermore, some of these control methods may require communication among different units when applied to clusters of DG. Better then to not require high-speed communications in a diverse microgrid, especially if each source is operated with its own unique control method. Complex protection protocols may also be necessary for successful operation of such a microgrid, although system studies have not yet been conducted to observe the impact of diverse technologies and control approaches on microgrid stability. Alternatively, if all DG devices connected to the microgrid adopt a common control structure that is independent of the prime mover, a consensus model that ensures stability may be achievable. Operation of the microgrid in both grid-connected and intentionally islanded modes offers a number of system-level benefits, particularly in operating regimes where the grid interface is weak or unreliable. Interface of a storage device capable of absorbing excess power when available and providing power to meet excess demand could also be integrated into the physical and control infrastructure. Features of the control strategy are described further in the following section.

Each of the generators is assumed to have a terminal voltage specified at its point of connection comprising of voltage ($V^{\dagger}$) and frequency ($\omega^{\dagger}$). This specification constitutes the voltage command that needs to be provided to each inverter-based DG, or to the field exciter and speed governor of each generator with a rotating machine primemover. A block diagram illustrating the derivation of voltage command for each inverter based source is shown in Fig. 3. The generation controller determines the incremental voltage magnitude and frequency information based on the real and reactive powers drawn from the generator. These incremental variables are added to their nominal values to determine a voltage command vector for its inverter. The instantaneous real and reactive powers at the generator terminal, denoted as P_L and Q_L, respectively, can be easily computed from the measured terminal voltages and currents. One solution that addresses all the design and operational challenges of a microgrid is a droop-based control algorithm applied uniformly irrespective of the prime mover (Illindala 2005, Piagi 2005). Other very similar approaches have been proposed (Engler and Soultanis 2005, Arulampalam, *et. al.* 2005), and one is used by the Uganda field demonstration (Brandt 2005). Droop-based control that is inherently provided by speed governors and field exciters are well known for rotating machines and will not be addressed further here (Cohn 1998). The use of droop-based active and reactive power controllers is also applicable for inverters on a uniform basis, thereby allowing a seamless interface of several generation sources into the microgrid.

Frequency regulator

An active power-frequency controller for a power electronic inverter based distributed uninterruptible power supply system proposed first by Chandorkar (Chandorkar 1995) has been further extended for control of DG inverters (Lasseter and Piagi 2000). A simplified block diagram of such an active power-frequency controller is illustrated in Fig. 4. It has a frequency droop with a proportional gain transfer function ($b > 0$), which provides the necessary load-governing functionality that is beneficial for paralleling several DG units. As may be observed from the figure, the reference set point for power, $P_{L\text{-}ref}$ is smoothed through a low pass filter with a corner frequency ω_G, before it affects any regulator operation. Following a step increase in load of P_L, its frequency would immediately drop by $\Delta\omega_{trans} = b\Delta P_L$. The regulator includes a frequency restoration loop whose function is analogous to the speed governor in a rotating machine generator, and the frequency is eventually restored to $\Delta\omega_{steady} = -b(1-K_{b\beta})\Delta P_L$, in an exponential fashion, with a time constant given by $1/\omega_b$. Note that parameter $K_{b\beta}$ ($0 < K_{b\beta} < 1$) represents the extent of inverter frequency restoration following a load transient. A very low value, i.e., as $K_{b\beta} \rightarrow 0$, denotes almost no frequency restoration whereas $K_{b\beta} \rightarrow 1$ denotes total frequency restoration. The transient and steady-state frequency deviations or droops are graphically represented in Fig. 5. Such frequency droop curves are useful in understanding the transient and steady-state sharing of total load demand in microgrid, as will be described in the following section.

Voltage regulator

A microgrid may include a mix of devices employing rotating prime-movers driving synchronous machines or other electrical energy sources interfaced through power electronic converters. In either case, their current capacity is limited by their design ratings. It is therefore necessary to control the reactive power drawn from any device in a microgrid, in addition to meeting appropriate power demands, i.e. maintaining the energy balance. In the case of synchronous generators, a field regulator that controls the terminal voltage naturally provides a mechanism for reactive power control. In the case of sources employing power electronic converters, this can be achieved by having a controller for regulating reactive power draw in addition to the active power draw.

A reactive power-voltage controller exploits the dependency of the reactive power supplied by the generator on the voltage magnitude at the load bus. Fig. 6 shows a block diagram of the proposed reactive power controller. As may be observed from Fig. 6, a simple feedback controller containing first-order lag is employed for the deviation in the reactive power. Unlike the active power-frequency controller, the reactive power-voltage controller does not contain a restoration segment. Moreover, it does not achieve a zero steady-state error but rather provides a voltage droop upon an increase in the reactive load demand. As seen in Fig. 6, the input labeled $Q_{L\text{-ref}}$ is the load set-point; i.e. the control input to shift the generator's voltage regulator characteristic in order to give the reference voltage (magnitude) at any desired reactive power output. The active modulation control, which varies the modulation index according to the dc bus voltage variations in the inverter, assists in providing a fixed voltage magnitude against load variation for some duration before other controls take precedence. It is possible to represent the steady-state voltage droop at a particular bus by voltage droop curves along the lines of frequency droop curves.

Following a step increase in reactive power Q_L at the DG terminals, voltage would drop by $\Delta V = \Delta Q_L/D_q$, at steady state. The transient following the step change in load or reference set point will follow an exponential variation, with a time constant given by $1/\omega_q$. The steady state relationship between voltage and reactive power can be represented by a straight line as shown in Fig. 7. The value of $Q_{L\text{-ref}}$ corresponding to a load ref. set-point of zero is $Q_{L\text{-ref}} = 0$. By changing $Q_{L\text{-ref}}$, the controller can be set to give nominal voltage at any desired reactive load condition. According to the convention employed, the load is inductive when it draws a positive reactive power, and capacitive when it draws a negative reactive power.

Generators in a Microgrid

The steady state power flow in an interconnection of ac voltage sources incorporated with active power-frequency and reactive power-voltage droop type controllers is well understood (Cohn 1984). Since each unit is allowed to 'float' its frequency and voltage outputs away from the nominal set points, the systems settles to a common frequency and a local voltage that ensures appropriate distribution of load among the units. In a microgrid, if each source has a particular power set point and is also interconnected to an infinite bus representing centralized grid, all the units synchronize themselves to the grid frequency. In this case, each source supplies its set-point power output, and the difference between total load demand and total set-point power levels flows in or out of the grid. In the absence of a centralized grid, three operational scenarios are possible: (a) one of the source is designated to be the peaking unit, which is set to have zero droop, and takes up the difference between power demand and the total set-point power levels; (b) the microgrid has at least one storage unit, which is set to have zero droop, and that takes up the difference; and (c) in the absence of peaking units and adequate storage, under-frequency sensitive load shedding needs to be incorporated to ensure energy balance. While these steady state power flow considerations may be addressed through prudent design, a more interesting question concerns the microgrid operational stability at an operating point where load and generation are adequately matched, which becomes the topic of further discussion here.

Each generator in a microgrid is assumed to be equipped with the reactive power-voltage (magnitude) controller along with the active power-frequency controller, and the dynamic behavior of a *chain* microgrid consisting of several such devices will be further investigated. In a chain microgrid, generators and loads are connected at various nodes along a distribution line as illustrated in Fig. 8(a). Such a configuration of interconnected generators would perhaps be most common along a radial distribution line emanating from a possible point of connection to a centralized grid.

The following assumptions are made in the analysis of dynamic behavior of the chain microgrid —(i) units operate within their maximum capacity limits; (ii) dynamics of the internal controls are fast compared to the external generation controls so that the internal controls can be neglected in power flow analysis; (iii) tie-lines between any two sources in the microgrid are purely inductive in nature; and (iv) the analysis is on linearized small-signal generator models. It is assumed that the tie line between any two buses i and j has an inductive reactance $X_{i.j}$. The operation of this chain microgrid in stand-alone configuration is analyzed further with grid-interfaced mode considered as a special case.

The state variable block diagram of the chain microgrid with the frequency regulator and the voltage regulator based on real power and reactive power feedback interconnected through an inductive tie line is shown in Fig. 8(b). This schematic directly depicts the control structure for two of the units, *viz.*, the k^{th} and $k+1^{th}$, with dashed lines indicating interconnections to the rest of the microgrid. In Fig. 8(b), $P_{ok.k+1} = \frac{V_{ko}\, V_{k+1.o}}{X_{k.k+1}}$, $D_{qtie.k.k+1} = \frac{2V_{ko} - V_{k+1.o}}{X_{k.k+1}}$ and $D_{qtie.k+1.k} = \frac{2V_{k+1.o} - V_{ko}}{X_{k.k+1}}$.

Using the state space model of the system, coupled with matrix methods of stability theory, it may be shown that sufficient conditions for ensuring stable operation of the microgrid are (Illindala 2005)

$$b_k,\ \beta_k,\ \omega_{Gk},\ \omega_{qk},\ D_{qk} > 0\ (k = 1, 2, \ldots, n) \tag{1}$$

$$\Delta V_{k\_max} < V_{ko}\ (k = 1, 2, \ldots, n) \tag{2}$$

Furthermore, stability of a possible interface of the microgrid with a centralized grid may be considered as a special case with the grid assumed to be an infinite bus with no incremental change in voltage, angle or frequency, *i.e.* $\Delta V_g = 0$, $\Delta\delta_g = 0$ and $\Delta\omega_g = 0$. Such a case is a radial network of *n* generators units connected to the infinite bus at one end and loads at each DG bus.

It has been shown in (Illindala 2005) that (1) and (2) also establish sufficient conditions that ensure stability of a chain microgrid with a centralized grid intertie.

In order to verify stable operation of the microgrid equipped with controllers described herein, a detailed computer simulation model of a benchmark system and a laboratory scale model of the benchmark system was built. A single-line diagram of the microgrid consisting of two generators is illustrated in Fig. 9. The generators represent any generic three phase ac sources, with appropriate frequency and voltage controls as described above. Under normal operating conditions, the generators, *viz.*, DR1 and DR2, share the load with the utility grid supply. However, when the utility supply is down, they are rated to provide all the energy requirements of at least the critical loads.

As seen in Fig. 9, the interconnection between any two generators is made by means of a tie-line interconnect that is made up of a three-phase contactor CN_1 with associated synchronizing and control logic circuitry. Likewise, a three-phase static switch SS_1 consisting of thyristors is utilized for the interconnection between the microgrid and the grid. Before connection, the three-phase voltages on both sides of the switch (CN_1 or SS_1) are synchronized. Not shown in Fig. 9 is the protection switchgear essential in safeguarding equipment and personnel.

The system having parameters given in Table 1 is simulated in Matlab® SIMULINK™ software. On the other hand, the controller is implemented in a digital signal processing platform, Motorola® DSP 56F805 Evaluation Board, in the laboratory experimental microgrid. Microgrid operation is carried out in three modes to demonstrate the generation controls. These are (i) single source in stand-alone mode, (ii) single source in grid-interfaced mode and (iii) two sources interconnected mode. Selected results are presented below during each mode of operation.

(i) Single source in Stand-Alone Mode

Results illustrating the frequency response against change in P_L and $P_{L\text{-ref}}$ are plotted in Fig. 10 and Fig. 11, respectively. The initial value of $P_{L\text{-ref}}$ is set at zero, and therefore at a load of 0.25 *p.u.* the frequency is 59.9375 Hz. As seen in Fig. 10, a step change in P_L from 0.25 *p.u.* to 0.5 *p.u.* gives a maximum transient deviation in frequency of 0.125 Hz (determined by controller gain b) from the initial frequency of 59.9375 Hz and a steady-state deviation in frequency of 0.0675 Hz [determined by $b(1 - K_{b\beta})\Delta P_L$]. The time-constant is determined as $(1 - K_{b\beta})/\omega_G = 500$ ms.

Fig. 11 illustrates the response for a change in $P_{L\text{-ref}}$ from 0 *p.u.* to 0.5 *p.u.* that reflects the current load condition. As against the response to change in P_L shown in Fig. 10, the step change in $P_{L\text{-ref}}$ gives a first-order lag response with a time-constant of $(1 - K_{b\beta})/\omega_G = 500$ ms and a steady-state deviation in frequency of 0.0675 Hz [determined by $b(1 - K_{b\beta})\Delta P_{L\text{-ref}}$].

(ii) Single source in grid-Interfaced Mode

The utility grid is simulated as an infinite bus using differential equations of three-phase voltage sources of fixed voltage amplitude and frequency in series with a tie-line of reactance $X_{tie} = 0.1$ *p.u.*. As it was observed that the grid frequency in the laboratory experiment test bed was 59.96 Hz, the same value also was employed in simulation. However, the nominal frequency set-point ω_o is maintained at 60 Hz. The results illustrating the response for a change in $P_{L\text{-ref}}$ from 0 *p.u.* to 0.5 *p.u.* at t = 5 s are plotted in Fig. 12. The load under this condition was 0.25 *p.u.*. Ideally, if the grid frequency were at 60 Hz, the generated power would have followed the $P_{L\text{-ref}}$ set-point; however, as the frequency is 59.96 Hz, the difference between $P_{L\text{-ref}}$ and generated power is determined from the steady-state droop curves as $(60\text{-}59.96)/[b(1\text{-}K_{b\beta})]$, which gives a value of 0.16 *p.u.* for $P_{L\text{-ref}} = 0$ *p.u.* and 0.66 *p.u.* for $P_{L\text{-ref}} = 0.5$ *p.u.*.

The generator frequency increases slightly for a short duration to enable higher generation but eventually returns to the grid frequency of 59.96 Hz. Fig. 13 illustrates the waveforms when the load P_L is changed from 0.25 *p.u.* to 0.5 *p.u.*. As seen in this figure, the DG supplies only the transient change in load, but at steady state, generation returns to a value determined by $P_{L\text{-}ref}$.

(iii) Two sources Interconnected Mode

Fig. 14 illustrates the results of DR1 response to a change in its local load P_{L1} from 0.2 *p.u.* to 0.4 *p.u.*. The corresponding waveforms for DR2 that has a local load of $P_{L2} = 0.4$ *p.u.* are displayed in Fig. 15. The load power set-points in both units are the same, *i.e.* $P_{L\text{-}ref1} = P_{L\text{-}ref2} = 0.4$ *p.u.*. Hence, as seen in these two figures the overall load is shared equally by the two DGs as the load burden of 0.4 *p.u.* for each DG is equal to its $P_{L\text{-}ref}$ set-point. As a result, the final steady-state frequency is 60 Hz, equal to the nominal frequency ω_o. However, the transient effect of load change P_{L1} is severe in local DR1 that its generation initially increases to more than the final steady-state value. In contrast, the remote DR2 increases its generation gradually to meet this increased overall load demand. Fig. 16 illustrates the DR1 load terminal voltage, DR1 current and the tie-line current between the two sources in steady state. As seen in the figure, since the two are supplying their local loads, the current through the intertie in simulation is zero. On the other hand, experimental results show a small amount of non-sinusoidal tie-line current, which is due to non-linear magnetizing current of the transformers of each unit.

Conclusions

In this paper, the operational dynamics of a diversified microgrid consisting of several generators has been presented. Each unit in the microgrid is equipped with droop-based active and reactive power controllers along with the internal voltage regulator. It is demonstrated that such droop-based controllers can support and allow seamless operation of a diversified microgrid against dynamic changes occurring in the system. Practical distribution system parameters have been considered in the system modeling and conditions for stability of the microgrid under such control has been presented in the paper. The capability of microgrids to provide reliable power with a diverse set of sources has been demonstrated by means of various case studies. This is shown in the form of response of the microgrid under interconnection and load change in different system configurations.

The features demonstrated in this paper illustrate the technical viability of a path based on microgrid consisting of several interconnected small sized DG units operating as a synchronous ac system in realizing rural electrification in developing economies. The case for such an approach being preferable over the centralized grid electrification was made in the paper based on studies and demonstration projects conducted by various international development agencies. To be sure, ensuring the stability of operation an approach based on the microgrid is among the key enabling requirements before any higher-level operational issues such as financing, ownership and market models can be envisioned. Other such key technical issues to be addressed include system protection, operator safety, pricing, metering, etc. Various research activities along these technical directions, as well as socio-economic and policy issues are in progress and represent an important deliberation by engineers and energy service professionals in meeting the MDG set forth by the international community.

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TABLE 1

EXAMPLE SYSTEM PARAMETERS

Symbol	Per unit value	Actual value 16 kVA, 208 V, 60Hz 3-phase
V_{1o}	1.0 *p.u.*	208 V
V_{2o}	1.0 *p.u.*	208 V
V_{grid}	1.0 *p.u.*	208 V
b	π rad./*p.u.*	π/16 rad./kW
$K_{b\beta}$	1/2	1/2
D_q	10 *p.u.*	0.94 kVar/V(peak)
ω_G	-	1 rad./s
ω_q	-	1 rad./s
L_f	-	0.97 mH
C_f	-	30 μF
V_{dc}	-	750 V

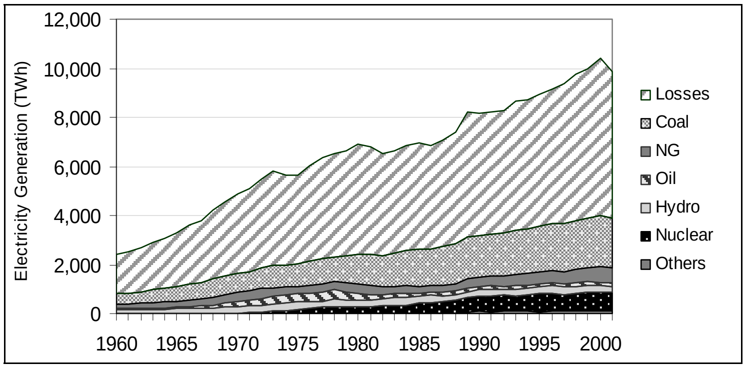

12,000
10,000
8,000
6,000
4,000
2,000
0
Electricity Generation (TWh)
1960
1965
1970
1975
1980
1985
1990
1995
2000
Losses
Coal
NG
Oil
Hydro
Nuclear
Others

Fig. 1

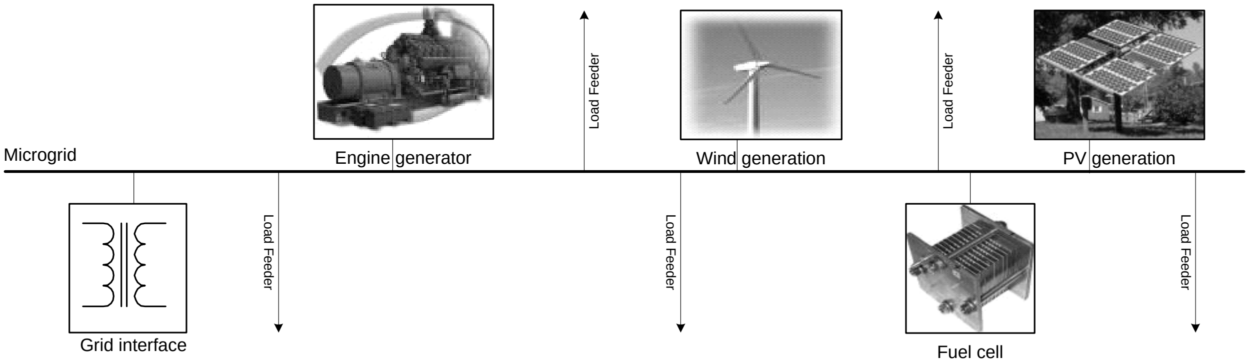

Microgrid
Engine generator
Load Feeder
Wind generation
Load Feeder
PV generation
Grid interface
Load Feeder
Load Feeder
Fuel cell
Load Feeder

Fig. 2

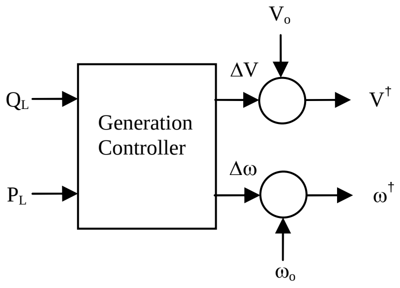


Fig. 3

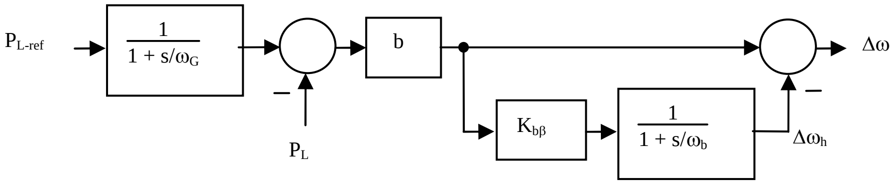


Fig. 4

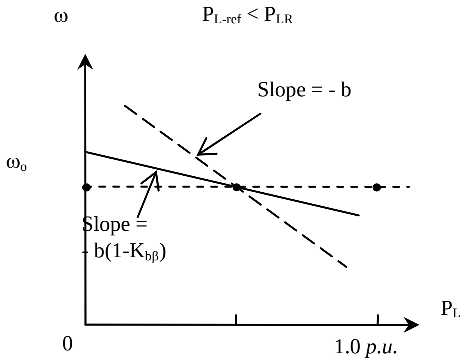


Fig. 5

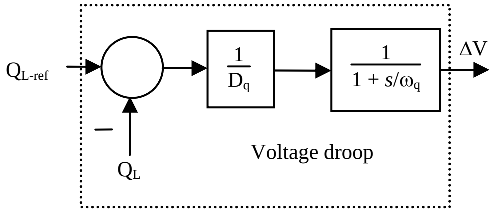


Fig. 6

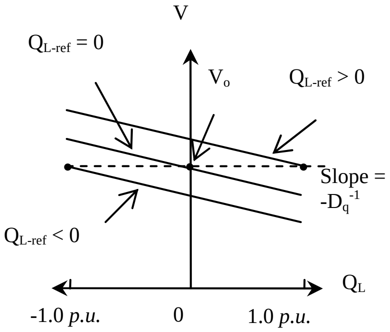
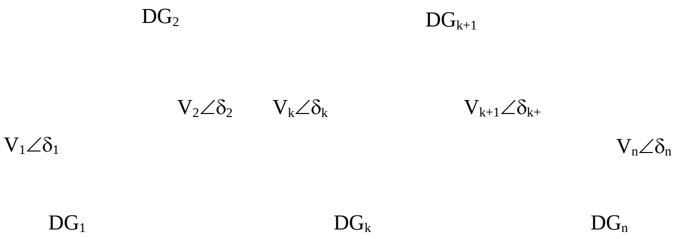
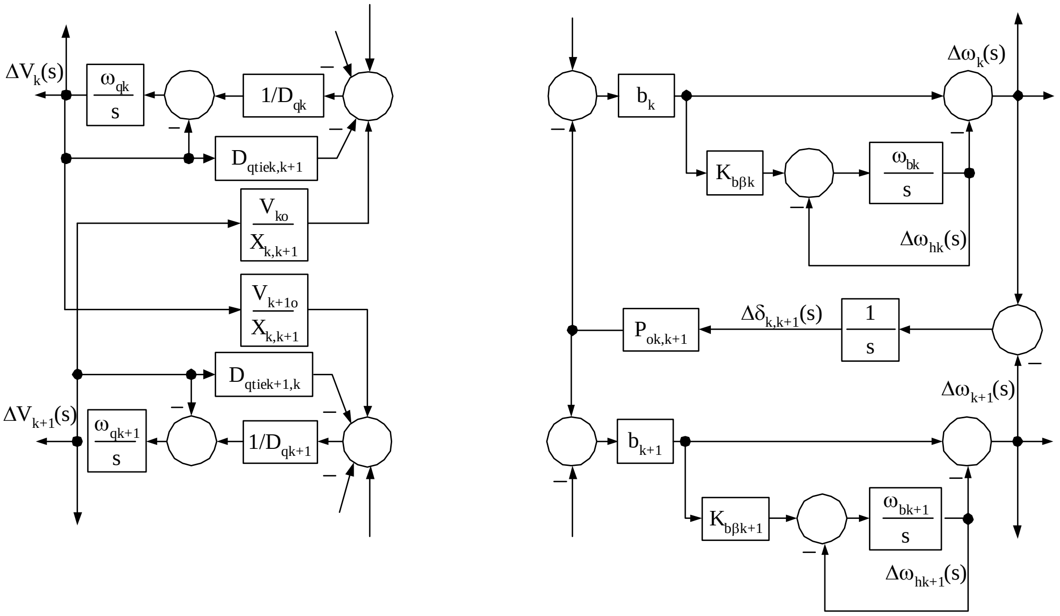

V
$Q_{L\text{-ref}} = 0$
V_o
$Q_{L\text{-ref}} > 0$
Slope =
$-D_q^{-1}$
$Q_{L\text{-ref}} < 0$
Q_L
-1.0 p.u.
0
1.0 p.u.

Fig. 7



(a) Single-line diagram



(b) Small-signal state-variable schematic under zero input conditions

Fig. 8

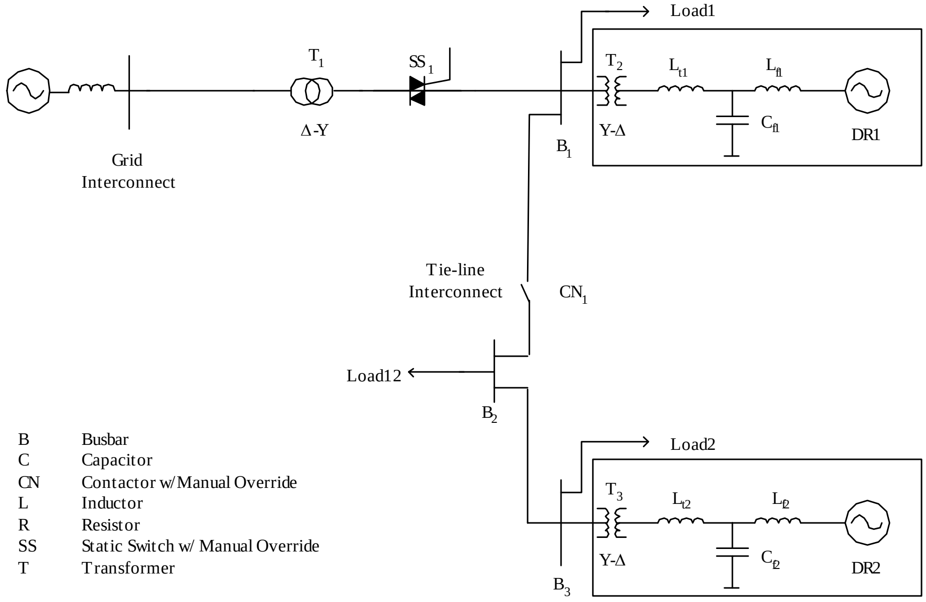
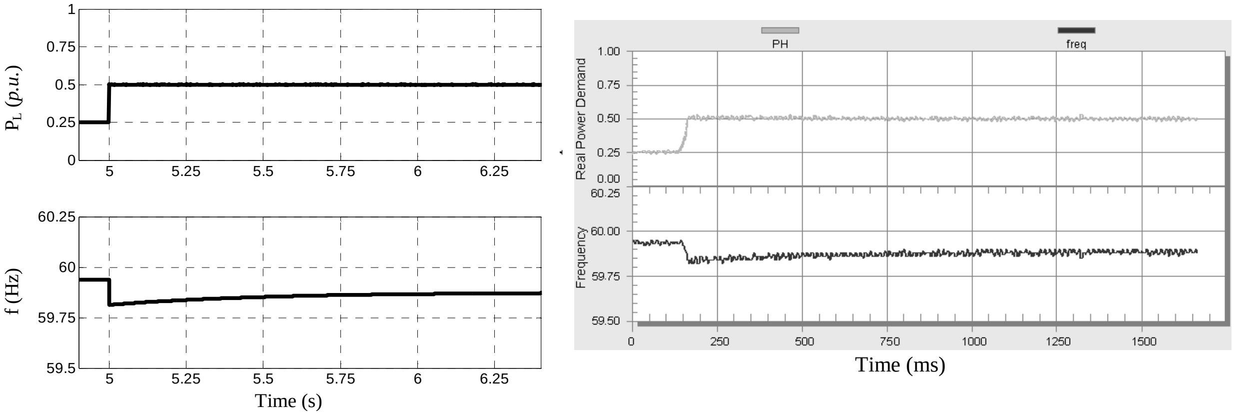

Load1
T1
SS1
T2
Lt1
Lf1
Y-Δ
Cf1
DR1
Δ-Y
B1
Grid
Interconnect
Tie-line
Interconnect
CN1
Load12
B2
Load2
T3
Lt2
Lf2
Y-Δ
Cf2
DR2
B3
B Busbar
C Capacitor
CN Contactor w/Manual Override
L Inductor
R Resistor
SS Static Switch w/ Manual Override
T Transformer

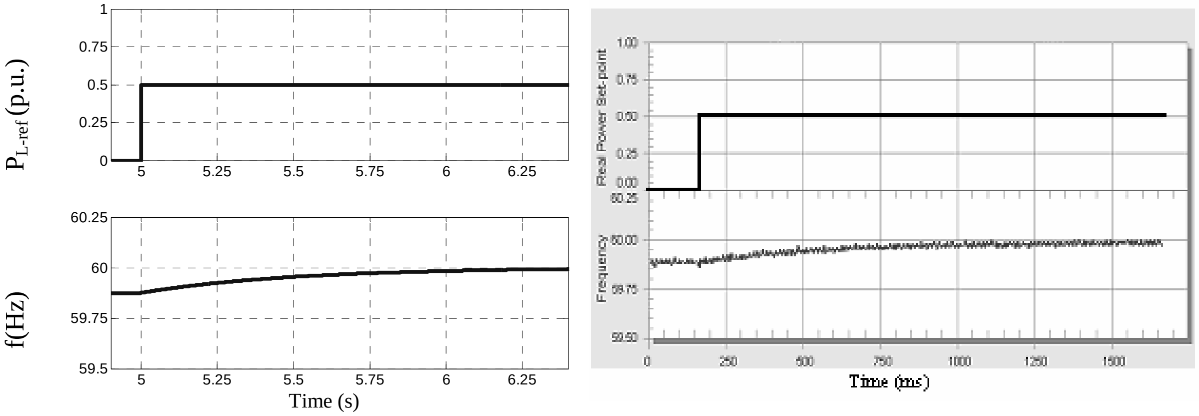
Fig. 9



(a) Simulation

(b) Experiment

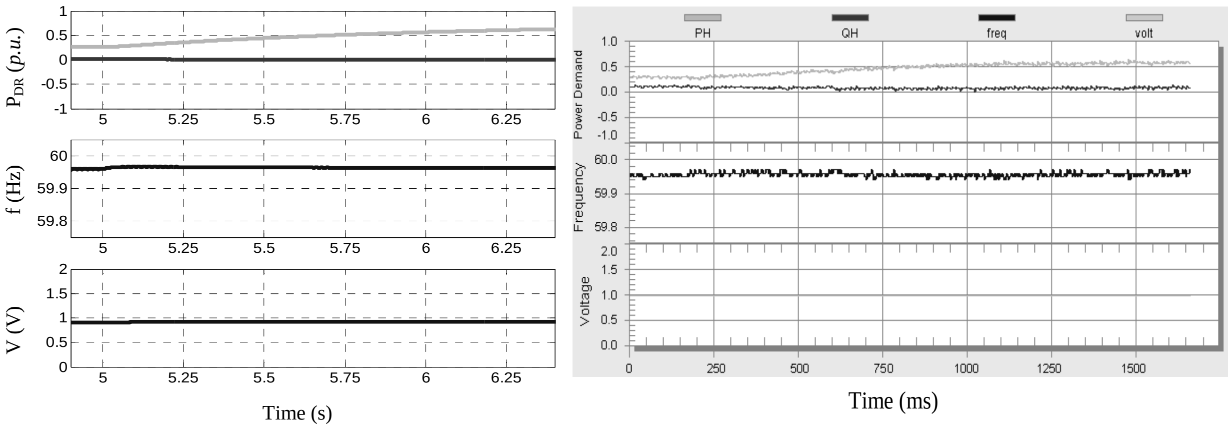
Fig. 10



(a) Simulation

(b) Experiment

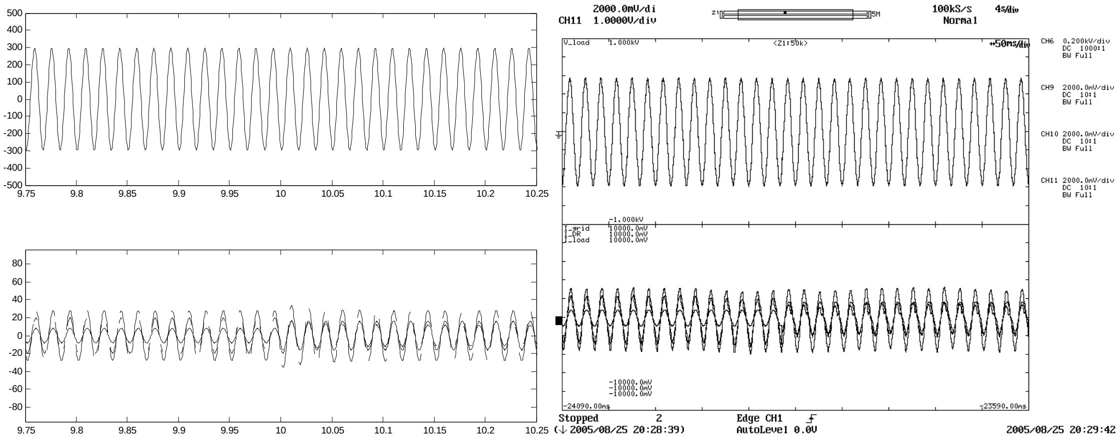
Fig. 11



(a) Simulation

(b) Experiment

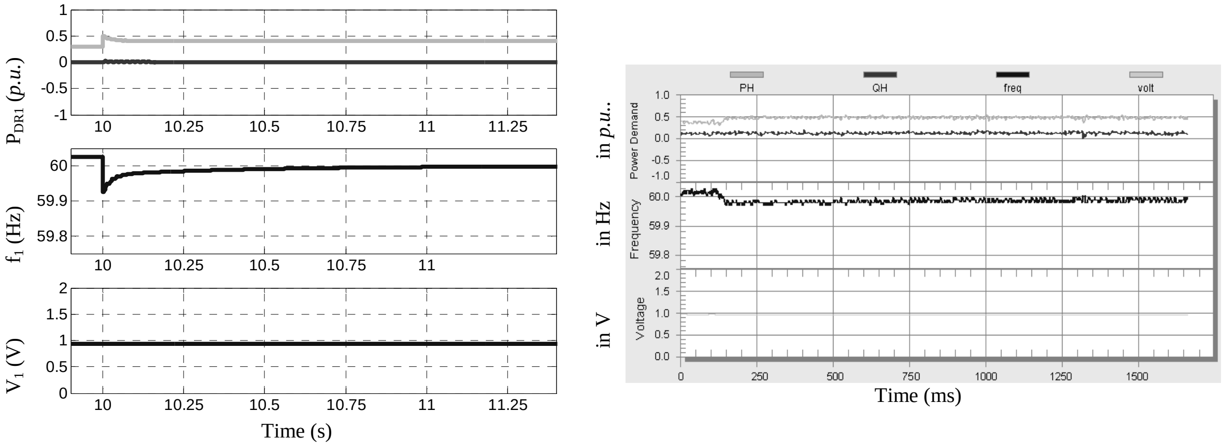
Fig. 12



(a) Simulation

(b) Experiment

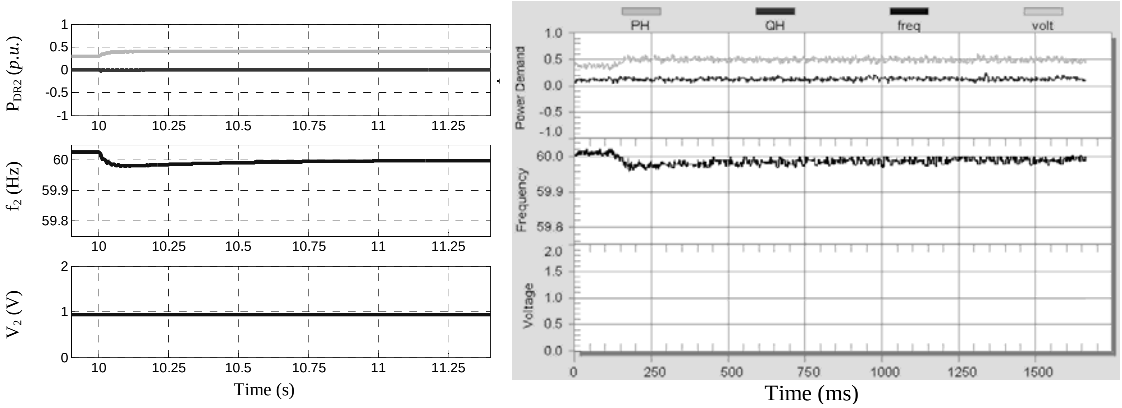
Fig. 13



(a) Simulation

(b) Experiment

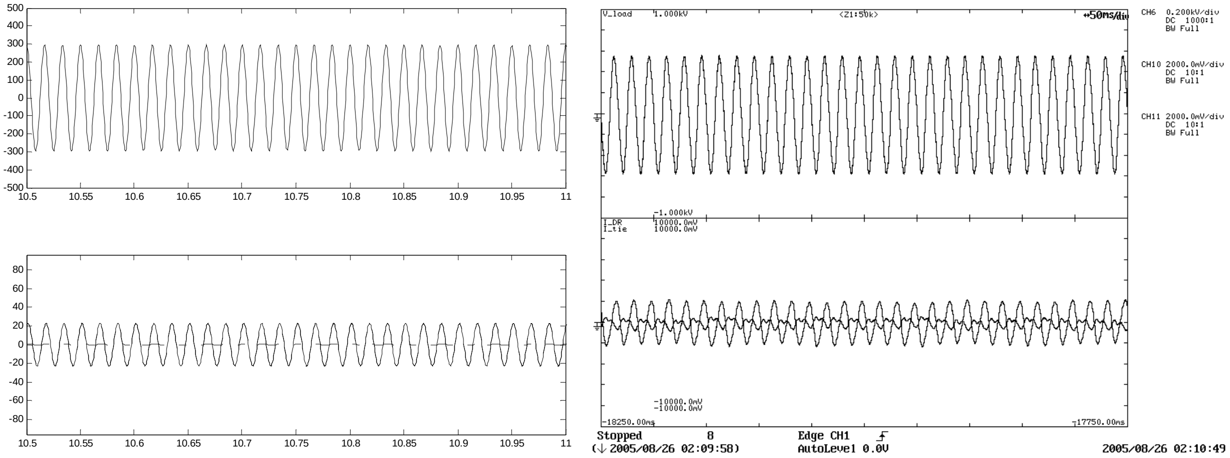
Fig. 14



(a) Simulation

(b) Experiment

Fig. 15



(a) Simulation

(b) Experiment

Fig. 16

LIST OF FIGURE CAPTIONS

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Fig. 8: Schematic models of DGs in a chain-configured Microgrid

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Fig. 11: Simulation and experimental waveforms showing response to a change in load real power ref. set-point $P_{L\text{-}ref}$ to match the load demand when the DG is operated as a stand-alone unit. (The y-axis scaling is identical for both simulation and experimental results.)

Fig. 12: Simulation and experimental waveforms showing response to a change in load power set-point $P_{L\text{-}ref}$ from 0 *p.u.* to 0.5 *p.u.* when the DG is connected to an infinite bus of frequency 59.96 Hz. (The y-axis scaling is identical for both simulation and experimental results.)

Fig. 13: Simulation and experimental waveforms illustrating the effect of load change at the DR terminals from 0.25 p.u. to 0.5 p.u. while it is operated in grid-connected mode. Load terminal voltage is the top waveform and in the bottom are the load current (solid), DR current (dashed) and tie-line current (dashdot).

Fig. 14: Simulation and experimental waveforms showing response of DR1 to a change in load P_{L1} from 0.2 *p.u.* to 0.4 *p.u.* when the two DGs are interconnected. (The y-axis scaling is identical for both simulation and experimental results.)

Fig. 15: Simulation and experimental waveforms showing response of DR2 to a change in load P_{L1} from 0.2 *p.u.* to 0.4 *p.u.* when the two DGs are interconnected. (The y-axis scaling is identical for both simulation and experimental results.)

Fig. 16: Simulation and experimental waveforms illustrating the two interconnected DGs supplying their local loads with zero power flowing along the tie-line. Load terminal voltage is the top waveform and in the bottom are the DG current (solid) and tie-line current (dashdot).