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Economical design of gate-commutated inverters for the grid-tied distributed generators

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The cost-effectiveness of small distributed generating resources is vital to the success of the high penetration of distributed generators within the microgrid concept. A common mechanism is the use of highly efficient inverters following the electrical storage systems. In this paper, the design of a basic inverter deploying a switching power amplifier is discussed. The amplifier acts like a power booster that taps the grid current as its frequency reference. The inverter transfer function was examined against voltage droop characteristics and was found to be in compliance with the IEEE 1547 standard for microgrid. The basic design simply utilizes the linear rise of voltage for the small triggering angle where the sinus of angle can be approximated as the angle in radians. This inherently performs a similar action such as a pulse width modulator for a narrow band. This inherent feature saves cost because it precludes the need for an extra power controller. © 2011 American Institute of Physics. [doi:10.1063/1.3582595]

I. INTRODUCTION

Microgrid architecture opens the path for decentralized generation (DG) systems to be independent clients of a large area power grid. The common expectation is standard compliant integration of less or zero greenhouse emissive DGs rather than fossil fuel driven generator counterparts.1 Microgrid structures inherently are characterized by a diversity of distributed energy resource (DER) elements involved considering the capital cost, operation cost, etc. The techno-economic impacts of microgrid on the investors’ market are more pronounced in Ref. 1. The IEEE standard 1547 on microgrid standards is emphasized on connection standards leaving the flexibility of choosing any technology that can be deployed. Another distinguishable property of a microgrid is the active central management of each intended island element, collectively called distributed resources (DRs). Every element is ring networked, which is passed a token from the central controller to determine its status within a fraction of a second. The active switches and breakers/couplers within the network are also kept ready to listen to the central controller and execute commands right away. This paper is divided into seven sections. In Secs. I–IV, the design requirements for the grid-tied inverters are discussed. In Sec. V, a basic economical model is proposed with an insulated gate bipolar transistor (IGBT) as a class C power amplifier.

II. MICROGRID INFRASTRUCTURE

Microgrid is conceived for safe integration of renewable sources to grid with some of the following benefits from its infrastructure:

• compliant to all connection standards in force (such as IEEE 1547 and local laws),
• integration absorbs fluctuation inherent in nature of the renewable sources,
• safely exports power to grid based on priority encoded request,
• managed to be isolated from the grid and run autonomously,
designed to run autonomously when isolated from the grid, and
radial islanded from the point of common coupling (PCC).

A microgrid infrastructure essentially is managed by a central controller programmed to do the following:

1. monitor DER (DGs and loads) status and process the input to synchronize operation (export power);
2. listen to grid request, manipulate the sensors' outputs, and respond accordingly (demand management);
3. isolate microgrid from the grid in case of faults in either domain (IEEE 1547 connection standard); and
4. maximize resource utilization—such as combined heat and power (CHP) [2].

Microgrid models are continuously being developed as a result of trends in economies and the availability/feasibility or cost-effectiveness of microsources to attract investors from private and incorporated organizations. It is quite simple in design and open for deployment of any technology compliant with connection standards. A typical microgrid single line diagram with photovoltaic energy sources is shown in Fig. 1, for example. The microgrid concept is advancing toward more maturity and, in the not too distant future, will be a widespread framework similar to cable internet service provider (ISP) in urban areas. The concurrent development phase faces the following minor challenges:

- cost of DGs,
- cost of energy storage systems and their round-trip efficiencies,
- cost of power quality control hardware,
- government incentive for promotion of this technology as a means of motivation.

Apparently, these issues cannot be considered as challenges for all kinds of DGs and primarily are related to design approach and the equipment market.

III. DR CENTRAL CONTROLLER

Microgrid controller incorporates synchronization algorithms, ensuring smooth and safe reconnection of the microgrid to the utility grid when the fault is cleared.2 The cost of this kind of controller is relatively high due to the DER elements’ deregulated output. The controller is aware of all DR characteristics within its network. The complexity of writing driver software for this controller involves the unique characteristics of individual DRs unless they are made identical and is not the best choice. The more DRs are in the network, the greater is the complexity of the synchronization. To resolve this issue, a utility grid reference should be input to the controller at all times.

Other complexities may arise when the DR controller needs to adopt a safety or system protection algorithm. The DGs in the network introduce considerable unbalance current and stray voltage among system neutral and ground nodes. Because the microgrid intended island should operate in grid isolation mode independently, the controller should be armed to counteract those unwanted effects.3

IV. VOLTAGE DROOP CONTROL

The integration of a large number of microsources into microgrid requires basic P-Q controls because voltage regulation is necessary for local reliability and stability.4 The goal is to prevent an unwanted swing of reactive power as well as the terminal voltage. Voltage control is also aimed at reducing possible circulating reactive currents among microsources,5 which is also a common issue for large synchronous generators in national grid.

However, this issue is not given importance for large synchronous generators because of their inherent high impedance on reverse flow. In the microgrid concept, this issue is almost a challenge due to the lack of this feature in small power electronic devices. Distributed generation with renewable sources may contribute to deregulated voltage regulation due its inherent stochastic nature if not mitigated.6 That is to say, the connection to the grid should be designed, inserting passive circuit elements (inductors and capacitors) under switching control at PCC to ensure correct operation. Consider the two connection configurations in Fig. 2. Both configurations appear very much alike, except that the parallel capacitive admittance has been placed in either side of the line inductance (actually a passive lumped inductance). This makes a large impact on

![FIG. 2. Connection configuration—(a) configuration 1 and (b) configuration 2.](image-url)
connectivity, which we shall see from the following analysis. From Consortium for Electric Reliability Technology Solutions (CERTS) concept of microgrid, the voltage and reactive power control should be such that it prevents circulating reactive current to flow in the microsources and thus eventually requires meeting the voltage set point in relation to the volt-ampere reactive (VAR) flow, as shown in Fig. 3.

Now, we can verify which one of the configurations has complied with this rule. Using typical per unit values, Figs. 4 and 5 are plotted simulating the circuit model shown in Figs. 2(a) and 2(b), respectively, using typical values of the elements. It is clear from the plot that configuration 1 satisfies the connection standard.

V. CIRCUIT MODEL OF GATE-COMMUTATED INVERTER

An example of a simple gate-commutated inverter circuit model is shown in Fig. 6. It is simulated with OrCAD® PSpice to determine input/output relation and to ensure this model
complies with the IEEE 1547 connection standards through voltage droop control. The IGBT model used in this example is available online from the respective manufacturer. First, let us verify whether the inverter output passive circuit conforms to configuration 1, our anticipated connection pattern (see Fig. 7). The full conduction current passes through the parasitic battery resistance $R_2$ and transformer inductance $L_1$. Clearly, the high shunt negative feedback resistance $R_4$ is very high to the input driving resistance $R_1$ and can be considered open, simplifying the equivalent small signal circuit model as well.

The output of Fig. 6 is shown in Fig. 8 in the frequency domain. The voltage and current amplification was measured from the input-output voltage and current plots. Figure 8 is actually the Fourier transform of the output voltage revealing the harmonic distortion. From the plot, it is clear that the amplification generates high, literally unacceptable, harmonics at the voltage output and, accordingly, in the current output to a resistive load. In order to mitigate the unacceptable harmonic level, Fig. 6 is modified by the addition of a first order band pass filter, as shown in

FIG. 4. VAR flow and terminal voltage relation with load power angle for configuration 1, as shown in Fig. 3.
Fig. 9. The filtered output delivers a more sinusoidal-shaped waveform by limiting the harmonic injection, as shown in Fig. 10. The above figure is redrawn below with its equivalent small signal at the top corner inside the figure box for a clearer comparison.

The noticeable difference in the circuit diagram, as shown in Fig. 9, is a higher inductance at the collector circuit mimicking a higher magnetizing inductance transformer core. A parallel tank circuit is added between the collector and the emitter, providing impedance matching and harmonic suppression capability at output. Using a single IGBT has an unavoidable trade-off also. Notice that the gate nonlinearity at low input current cause series voltage drop (similar to diode forward voltage drop), which introduced the major asymmetrical distortion at the output waveform. With a push-pull arrangement, the zero crossing distortion will take the place of this asym-
metry such that only the odd harmonics will exist and affording better filtration. Using polarity selective amplification (a combination of a flip-flop, a demultiplexer, and two basic amplifiers), the asymmetry can be minimized, but the cost will rise proportionately.

From Fig. 10, it is obvious that power spectral density (PSD) at output is boosted significantly (60 Hz) when the harmonics are reduced. Note that stiffing the harmonic suppression requires additional passive elements in the circuitry; that is to say, meeting power quality requirements will be traded-off by the additional cost of the inverters. However, if high penetration is expected, then the injected harmonics from different inverters may be resonated, risking poor power factor in the load proportional to the sensitivity of the node where it is connected.
In the phasor diagram shown in Fig. 11, the triangle OPQ represents the inverter input circuit (IGBT base), and the triangle QRS represents the output circuit (IGBT collector). The figure shows that the output voltage can be made leading by reducing the input reactance, thus improving the input power factor. A capacitive filter will work for that, but care should be taken in designing the input circuit such that it does not generate local oscillation close to grid voltage frequency.

FIG. 8. Harmonics at the output the circuit configuration, as shown in Fig. 7.

FIG. 9. Inverter output circuit design to suppress harmonic distortion.
VI. MICROGRID DG MODELING

Modeling the DG sources in microgrid is essential to writing an operation routine for an event scheduled charge discharge of any grid-tied electrical storage system. For example, the profile data

FIG. 10. (a) Voltage waveforms at input and output. (b) Fourier transform of the input and output voltages.

FIG. 11. Phasor diagram of the inverter’s input/output.
for photovoltaic output power can serve as the basis for a software model that can be used to simulate a hardware-in-loop system. As the sun (not sunlight) is 100% determined by the timing of light energy, the only probabilistically distributed uncertainty in the PV output is the weather imposed conditions. The profile is very local and may not be interchangeable for an identical setup in a different location. This is equally true for all other renewable sources, but the likeliness of similar source models being identical is common. The model need not be accurate because the purpose of simulation is not to justify a unique system; rather, it is used to estimate DGs’ average outcome or sustainability.

When modeling is a concern of microgrid design, two major areas are considered.

- **The microgrid infrastructure.** This is the so-called application aspect of microgrid. For instance, industrial microgrid operates in medium to high level voltage and may have multiple distribution transformers. The microsources can be residual heat driven turbo generators or very large battery storage systems. Industrial microgrid also may include VAR generators, synchronous alternators where the torque from huge wind power driven variable speed induction motors can be shared. On the other hand, residential microgrid usually operates at a low voltage level and usually includes voltage/current source inverters, smaller size renewable microsources. The distinguishable differences are the voltage levels at different nodes of the islanded microsources. Residential microgrid realization is more dependent on available resources and essentially has similar applications such as the use of uninterruptible power supply (UPS) in natural disaster scenario.

- **The microsources.** The nature of microsources’ intermittent output implies any specific coordination to mitigate the oscillation among microgrid islands. Here, coordination means utilizing the complementary nature of the microsources’ output to meet continuous demand. For example, a wind turbine may yield more power in the evening, offsetting the ceasing output of the PV panel during that time. This phenomenon is distinctly addressed in the multiagent system model of DER (Ref. 7) deploying intelligent resource management.

VII. CONCLUSION

Gate-commutated inverters are less expensive than the pulse width modulation (PWM) type inverters that are very common in industrial applications, where power quality requirements cannot be compromised, but tighter power quality requirements may add to the cost of inverters and easily discourage small-scale residential customers. The design presented in this paper demonstrates feasible ways to improve the power quality of a typical gate-commutated inverter without introducing sophisticated circuitry. On the other hand, most of the residential loads—water pumps and HVAC equipment—can tolerate degraded power quality without losing much life. Thus, gate-commutated inverters are an economical alternative to PWM type inverters for residential microgrid applications.