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State of the Art of Power Converter Topologies for Distributed Generation Systems

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Abstract— **Energy technologies have a central role in social and economic development at all scales, from household and community to regional, national, and international. Among its welfare effects, energy is closely linked to environmental pollution and degradation, economic development, and quality of living. In this paper, we will give a look at important of distributed generation as an approach in integration of green and renewable energy sources. This will put into focus the importance of inverter topology for distributed generation. Furthermore, we present the concepts that have been reported in the literature. The reference section at the end of this paper will give a wealth of information sources for readers. Finally, we will present the important system topologies that we will use in a later work.**

Keywords—distributed generator; power converter; voltage controller; current controller;inverter.

I. INTRODUCTION

The need for electric energy is never ending. Along with the growth in demand for electric power, sustainable development, environmental issues, and power quality and reliability have become concerns. Electric utilities are becoming more and more stressed since existing transmission and distribution systems are facing their operating constraints with growing load. Under such circumstances, distributed generations (DG) with alternative sources are an urgent task. Distributed generation entails using many small generators of 2 to 50-MW output, situated at numerous strategic points throughout cities and towns, so that each provides power to a small number of consumers nearby and dispersed generation refers to use of even smaller generating units, of less than 500-kW output and often sized to serve individual homes or businesses. Later publications tend to combine the two categories into one (i.e., distributed generation), to refer to power generation at customer sites to serve part or all of customer load or as backup power, or, at substations, to reduce peak load demand and defer substation capacity reinforcements.[1]

Distributed generation is not a new concept since traditional diesel generator as a backup power source for critical load has been used for decades. However, due to its low efficiency, high cost, and noise and exhaust, a diesel generator would be objectionable in any applications but emergency and fieldwork, and it has never become a true distributed generation source on today’s basis. What endows new meaning to this old concept is technology. Environmental-friendly renewable energy sources (such as photovoltaic devices and wind electric generators), clean and efficient fossil-fuel technologies (such as micro-gas turbines), and hydrogen electric devices (fuel cells) have provided great opportunities for the development of distributed generation. Gas-fired micro-turbines in the 25 to 100-kW range can be mass produced at low cost using air-bearing and recuperation to achieve reasonable efficiency at 40% with electricity output only and 90% for electricity and heat micro-cogeneration. Fuel cells have the virtue of zero emission, high efficiency, and reliability and therefore have the potential to truly revolutionize power generation. The hydrogen can be either directly supplied or reformed from natural gas or liquid fuels such as alcohols or gasoline. Individual units range in size from 3 to 250 kW or even larger megawatt size. The fastest growing renewable energy source is wind power. On a worldwide basis, available wind energy exceeds the presently installed capacity of conventional energy sources by a factor of four. Photovoltaic systems can be used in a variety of sizes and show better potentials in those areas with high intensity and reliability of sunlight. Besides these power generators, storage technologies such as batteries, ultracapacitors, and flywheels have also been significantly improved. Flywheel systems can deliver 700 kW for 5 sec while 28-cell ultracapacitors can provide up to 12.5 kW for a few seconds. To apply the above generation and storage technologies in a DG environment involves new technical problems.[2]

DG units require power electronics interfacing and different methods of control and dispatch. A DG unit should be able to operate under either island mode or grid-connected mode. In island mode, it should provide steady, low regulation error, low total harmonic distortion (THD), and fast response AC power under various load disturbances. In grid-connected mode, it should give steady-state decoupled active power P and reactive power Q control and proper behavior under connecting, disconnecting, and reclosing operations. If multiple units are paralleled on the same terminal or bus, correct load sharing should be performed among the units. A DC/AC voltage source inverter (VSI) is the most widely used interface for DG units, which involves many topology and control aspects under different operating conditions. Only with satisfactory control performance of each individual unit can paralleling two or more inverters or connecting one or more

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inverters to the power system be conducted. This involves P and Q control under various local load characteristics and operating conditions. As stated above, the tremendous complexity in the power electronics interfaces for DG units creates many research problems as well as many possibilities to advance technologies. Many of the problems have been solved or partly solved, while many are still left unsolved or even unfound. In general, a practically functioning DG system has to properly solve possible technical problems in the following three categories: control of a single inverter unit with quality voltage output in island mode, control of line real and reactive power flowing between a DG unit and the utility grid in grid-connected mode, and control of front-end power generation or conversion for high performance and low overhead. Due to the great potential of DG technologies, these research problems deserve special attentions and warrant careful further investigations.[3]

In this paper, the above problems will be addressed by presenting the following information problem descriptions, and discussions of literature review will be given within the scope of research as mentioned above about DG control technologies and the existing solutions will be evaluated. Specific research problems will be described.

II. VOLTAGE AND CURRENT CONTROL OF INDIVIDUAL INVERTERS IN ISLAND MODE

In island mode, an inverter unit needs to control load voltage as it is supplying local load with quality power. There are a number of control methods that are used to control the inverter voltage. These methods are: PID control, model-based linear control, robust control, sliding mode control, and internal-model-principle-based control.[4]

A. Conventional PI Control Method

This is a classical method of voltage control of an inverter based on proportional-integral (PI) regulation under stationary reference frame where the PI regulators have to track sinusoidal varying inputs. Since a PI controller only guarantees zero steady-state error under DC reference input, this control technique cannot be convincing in control performance. This method has been extended by using proportional control plus model-based compensation. It does not utilize the information that the reference input is a 60-Hz sine wave, so that the control design has to be able to handle arbitrary input, which is unlikely to yield a good control performance for DG applications. Another variation in this method is designed based on a dual loop proportional control scheme for single-phase half bridge inverters in island mode.[5]

B. State Feedback-Based Controls

Standard linear control theory has been employed to control the inverter voltage. One approach is based an analog control algorithm using a canonical lead-lag compensator based on a transfer function model. The extension of this method is a state-space-model-based state feedback control technique. This method has also used a linear quadratic index on top of traditional linear state feedback control to achieve optimized performance.

C. Robust Control

H∞ design procedure can be used for a inverter control to improve robust stability under model uncertainty and load disturbance. However, the control performance under nonlinear load is not satisfactory.[6]

D. Sliding Mode Controls

Sliding mode control has also been used in inverter control due to its robustness and overshoot-free fast tracking capability. This technique is used with discontinuous control and discrete control and implementing it with a digital controller. In this technique, the control variable in each sampling period is calculated based on the plant model and feedback quantities. The control is continuous and the chattering problem does not exist. The results show good performances under both linear and nonlinear loads. This method has been extended using deadbeat current control and proportional voltage control. The deadbeat control concept is the same as the discrete-time sliding mode control. [7]

E. Internal Model Principle and Reference Frames

This method states that asymptotic tracking of controlled variables toward the corresponding references in the presence of disturbances (zero steady-state tracking error) can be achieved if the models that generate these references and disturbances are included in the stable closed-loop systems. Actually a PI controller is an example of using the internal model principle in that the integral term models the mode of a step input and therefore results in zero steady-state error tracking DC reference input. However, this is no longer true if the reference signal is an AC quantity. In three-phase systems, reference frame transformation from a stationary ABC frame to a synchronous rotating dq reference frame can transform AC quantities in synchronous frequency into DC quantities that can be handled by a PI controller. It has to be noted that a synchronous reference frame can only transform components in the synchronous frequency into DC while all other frequency components are still AC. In three-phase DG systems, if the fundamental frequency components are transformed into a synchronous reference frame, all harmonic components are still AC quantities in the same synchronous reference frame.[8] This method has been used as a proportional control scheme for a three-phase inverter based on small-signal analysis in a synchronous reference frame only for the fundamental frequency. The method has been utilized as a nonlinear prediction technique to handle harmonic components in a fundamental synchronous reference frame. Due to the limitation of a single fundamental synchronous reference frame in handling harmonics, ideas have been raised for having multiple rotating reference frames corresponding to multiple frequency components including the fundamental and harmonics as well. This method has been used as a three-phase inverter controller with multiple synchronous reference frames. This technique requires information of magnitudes and phase angles of each frequency components from phase-locked loops (PLL), which increases the complexity of the solution. The proposed control technique is also based on multiple rotating reference frames trying to convert multiple frequency components into DC. This technique needs gain and phase correction in each reference frame, which also increases the overall complexity of the solution. In general, the multirotating frame type of technique provides a systematical solution to achieve zero steady-state error for multiple frequency components while the trade-off is the high complexity. [9] The internal model principle can be better used in a different way where the modes of all frequencies of interest are modeled in the same reference frame so that the steady-state tracking errors of all modeled frequencies can reach zero. Typically, a stationary reference frame for three-phase systems is used where all AC frequency components remain AC since there is no necessity to take advantage of DC quantities given the capability of handling AC directly using the internal models. Clarke's transformation from ABC stationary reference frame to $\alpha\beta 0$ stationary reference frame provides decoupling between the axes and enables independent modeling and control in each dimension and hence it is widely used. There is no reference frame issue at all in single-phase systems since all original quantities are in stationary reference frame inherently. Repetitive control is a specific implementation of internal model principle in a single reference frame, which eliminates periodical tracking error or disturbance whose frequency is less than half the sampling frequency. For a single-phase half bridge inverter, a standard single-loop repetitive controller can be designed and implemented in discrete time, which yields acceptable steady-state performance but slow transient response. The method can be extended by using a state feedback plus integral controller that has been added to provide better response to instantaneous disturbances and the idea has been proved effective by the presented results. Different from repetitive control, the internal model principle can be used only to eliminate periodical tracking error and disturbance with specified frequency, which is generally, enough for inverter control for DG applications since THD is nearly caused by low-order harmonics. All works in this area take advantage of the concept of generalized integrator which expands the functionality of the integral term of a PI controller for multiple frequency components in the same reference frame. The method is used with servo controller and linear quadratic optimization in their control approach for a three-phase inverter. This approach is based on the robust servomechanism control theory that yields a THD of 2.7% under nonlinear load with a crest factor of 3:1, which is satisfactory.[10]

III. THE SYSTEM TOPOLOGY

A. *Robust Stability*

A feedback control system is said to achieve robust stability if it remains stable for all considered perturbations in the plant. In feedback controlled PWM inverter systems (e.g., an inverter-based three-phase distributed generation unit operated in island mode), load disturbance, noise, and parametric uncertainty of the electrical components in the circuit are the major plant perturbations that have significant impacts on both system stability and performance. [11]

B. *Pulse Width Modulation Techniques*

Pulse width modulation (PWM) is an essential but not only technique to control a switched-mode power converter using self-commutated devices, including the DC/AC inverter and AC/DC rectifier mentioned above. Alternative modulation techniques include the hysteresis technique and delta modulation where the switching frequency is not a constant, which tends to cause harmonic distortions in its output wave form and therefore limits the application of such techniques. A number of PWM techniques have been developed and used in power converter controls to generate sinusoidal waveforms. However, only three of them have become standards and have most often been applied into practice: naturally sampled sine PWM (NSPWM), uniformly or regularly sampled sine PWM (USPWM), and space vector PWM (SVPWM). NSPWM uses a modulation signal (i.e., the sine wave) to be compared to a high-frequency carrier (i.e., a triangle waveform); and the compared result, which is a logic signal, is used to determine the ON or OFF state of the power switches. NSPWM does not control the position of the pulses it generates in each cycle, and the minimum pulse width is not controlled. USPWM still uses a triangle carrier signal at switching frequency, but it only uses the comparison result to determine the ON or OFF duration of the switches but not the pulse position. The pulse position is uniformly controlled—for example, put at the center of each switching cycle. SVPWM maps eight switching patterns of a three-phase full-bridge converter into six 60° apart space vectors on the same plane and two 0-axis vectors perpendicular to the plane, and a reference vector on the plane is used as a modulation signal and determines the time average of these switching patterns in each PWM cycle. If the reference vector rotates on the plane from sector to sector, a sine wave is modulated in the pulses. All inverter control techniques listed above are based on an assumption that the DC bus voltage is fixed and well-regulated or that its change does not affect the control on the load side. However, this assumption is not always true in a DG environment where fuel cells, wind generators, or photovoltaic modules could be the source with an unregulated or poorly regulated DC voltage. Even though in most cases, a properly developed PWM scheme can compensate for the DC bus voltage change inherently so that the load side cannot encounter any effect of the DC voltage change, this change may still undermine the performance of PWM inverter under some situations. [12]

C. *Line-Interactive Operation of Inverters and Control of P and Q*

Line-interactive inverter systems with a local load need active filtering capability of the inverter to compensate for the effect of harmonic corrupted load current by pumping compensating current into the power system through real-time control. In this type of application, the goal is to make the line current as sinusoidal as possible. The inverter control technique for photovoltaic systems connected with utility grid can use standard space vector PWM with only a linear local load. A special topology, referred to as series-parallel topology, utilizes power dragged from a utility grid through a rectifier to condition the utility line current through an inverter. The rectifier is connected to the utility grid through a transformer in series with the power line, and the inverter is paralleled with the power line; this is how the topology is named. [13]

D. *Current Quality of Line-Interactive Inverters*

When an inverter is connected to a power system, the terminal voltage is governed by the power system but the current waveform is still controllable. Although current wave form control is one of the goals of the line-interactive inverter

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control, power control (including P and Q controls) is the eventual objective to be achieved by a power electronics interface in DG environment. DG systems may have significant impact on power system stability if not properly compensated in reactive power. Also, DG systems can have significant impacts on transmission system stability at heavy penetration levels, where penetration is defined as the percentage of DG power in total load power in the system. A DG unit affects the system stability by generating or consuming active and reactive power. Therefore, the control of power on DG system determines its impact on its local the utility grid. If the power control performs well, the DG unit can be used as means to enhance the system stability and improve power quality; otherwise it could undermine the system stability. [14]

A line-interactive uninterruptible power supply (UPS) is able to pick up the load at power system failure and reverse power flow direction to battery charging when the power line is restored However, the power flow control in line-interactive UPS does not match the requirement of DG systems by far. A three-phase AC‑DC‑AC power conversion system can also be used for interfacing small wind turbines to utility grid. [15]

This system has been developed for both island and grid-connected operations. The power control concept for synchronous generator paralleled with power system into the application of grid connected inverters, that active power P can be controlled by adjusting phase angle of output voltage and reactive power Q, can be controlled by adjusting the magnitude of the output voltage. This can be accomplished by an inverter control technique for line-interactive operation where P and Q can be separately controlled through closed-loop control. [16]

A power control method can also be used for a grid-connected voltage source inverter that achieves good P and Q decoupling and fast power response. However, this approach requires an interface inductor to be connected between the DG output terminal and power system, whose inductance value is assumed known. The existence of the interface inductor creates a higher voltage magnitude change at the DG terminal. [17]

This higher voltage at DG terminal will facilitate the regulation of active power, P and reactive power Q. A different power control strategy based on frequency and voltage drop characteristics of power transmission, which allows decoupling of P and Q at steady state, can also be implemented. In this method, power regulation errors ΔP and ΔQ are used to generate output voltage phase angle and magnitude changes, respectively, which decouples P and Q controls in steady state.

IV. NEWTON–RAPHSON METHOD

The Newton‑Raphson Method is an iterative root-finding algorithm that uses the first few terms of the Taylor series of a function f (x) in the vicinity of a expected solution. The Newton‑Raphson Method is widely used in solving power flow problems due to its fast convergence property. This technique has also been used in line interactive power converter systems. The Newton‑Raphson power flow analysis is performed in a power system involving AC‑DC‑AC switch mode power converters. [18]

A. *Front-End Rectifier Control in Controlled AC–DC–AC Systems*

If we look one step back toward the feeder of the inverter DC bus, we can find that significant portions of the feeders are controlled by AC/DC rectifiers. In a DG environment, the input AC source can be any gas- or wind-turbine-driven generators or other AC and/or DC systems. No matter what source is used, a balanced 3-ph input current with low THD is desired, which is called a power factor correction (PFC). There are many existing PFC rectifier topologies. For high-power applications, especially when high performance is required, a continuous conducting mode (CCM) boost rectifier is usually used due to its high efficiency, good current quality, and low EMI emissions. A standard CCM boost rectifier has a full-bridge topology, exactly identical to a three-phase full-bridge inverter. This type of rectifier is controlled by an outer DC voltage control loop and an inner input current control loop, where the voltage regulation error is used to generate the input current command for the inner loop. When the DC voltage is boosted (i.e., greater than the input line voltage amplitude), this rectifier yields excellent control performance. The CCM boost rectifier is also called the PWM rectifier, the boost rectifier, or the controlled rectifier in the literature.[19]

In three-phase four-wire systems, a split DC bus inverter topology can maximize its performance with a three-level controlled rectifier regulating both the top and bottom half voltages of the DC bus. A full-bridge CCM boost rectifier as discussed above can serve the purpose with a modified voltage regulation scheme based on the standard approach described above. Besides the full-bridge topology, VIENNA rectifier topologies can also be used. A VIENNA rectifier is a three-phase three level rectifier based on a traditional uncontrolled diode rectifier with additional input inductors and six active power switches to achieve the neutral point voltage control. A drawback of the VIENNA rectifiers compared to the full-bridge topology is that it does not allow bidirectional power flow.

In three-phase three-wire systems, if a full-bridge controlled rectifier is used together with an inverter, the impact from the inverter side needs to be taken care of for better control of the rectifier. One typical impact frequently seen is an unbalanced load on the inverter side. It should be noted that the DC voltage ripple problem is caused by either unbalanced inverter load current or unbalanced input voltage supply. However, their control goal was to minimize the DC link voltage ripple instead of improving the input power quality. One can focus on improving instantaneous power balance between the input and output of a rectifier‑inverter system and minimizing the DC coupling capacitance to reduce the cost. The lower the DC coupling capacitance, the better the instantaneous power balance the system could yield. However, this is only desirable under balanced load. Once the inverter load is unbalanced, it is apparent that the steady-state inverter output power is no longer a constant, and neither is the inverter input DC power.

A switching function concept for power converters can be used to show the existence of harmonics in DC bus voltage. However, none of these works quantified the harmonic components analytically and used the result to analyze the ripple problem mentioned above. [20]

The control-related issues are major aspects of single-unit operation of switching mode utility interface for DG systems.

Single-unit voltage and current control is the basis for DG unit operations in either island mode or grid-connected mode. Many control theories have been applied in this area, and it has turned out that sliding mode control and internal-model-principle-based controls yield better performance under nonlinear load disturbances. Although multiple rotating reference frame techniques can handle the harmonic load disturbances, the stationary-reference-frame-based techniques yield the same performance while cost less overhead. Although the four-leg inverter topology in a three-phase four-wire system performs better than a split DC bus topology in some aspects, the latter requires easier control and uses less power switches and therefore remains an option.

The robust stability of an inverter control technique is an important issue in practice, given parametric uncertainties and load disturbances. Structured singular value μ -based analysis provides evaluation of closed-loop robust stability and the stability margin information and hence can be used as a guideline for control gain tuning.

Uniformly sampled PWM can be made identical to space vector PWM with 0-axis signal injection. Space vector PWM can perform 0-axis control if magnitudes of the two 0-axis vectors are made different. This allows SVPWM to be used in three-phase four-wire systems, but such application has not been seen in the literature. [21]

Power control of a DG unit is necessary under grid-connected running mode. Experimental results about line-interactive inverters are only seen for active filtering purpose or united power flow controller (UPFC) topologies in the literature, while those for power control of DG with local load have not been seen in publications. The Newton–Raphson Method is known as a good nonlinear equation-solving tool and is widely used in power flow problems, including switching mode power converter involved problems, all of which are performed off-line.

As far as the front-end source of a DG unit is concerned, a controlled rectifier should not only provide well-regulated DC voltage but also perform PFC and take balanced input current. In a three-phase three-wire system, unbalanced inverter load may introduce ripple on the DC bus and cause unbalanced input current problem for the rectifier, but no further solution has been reported.

The switch-mode inverter-based DG interface is of interest in (a) island mode, the voltage control problem of a DG inverter with three-phase four-wire transformer less topology for quality power supply to the local load; (b) grid-connected mode, the real and reactive power flow control problem in existence of local load; and (c) a three-phase three-wire AC–DC–AC system, the front-end PFC rectifier control problem with unbalanced inverter load. In this book, all of the above problems will be addressed by proposing a series of new solutions with detailed analysis, simulations, and experimental results. [22]

B. *Voltage and Current Control of A Three-Phase Four-Wire-DG Unit in Island Mode*

A three-phase three-leg inverter with split DC bus is one topology to implement three-phase four-wire system with a neutral point seen by the load. Compared to a three-phase three-wire system, it does not have the isolation transformer and provides three-dimensional control. Compared to a three-phase four-leg topology, it saves two power switches and reduces control complexity. Therefore the control problem of the three-phase three-leg inverter with split DC bus is of interest in DG applications. Although a three-phase three-leg inverter with split DC bus topology is a combination of three half-bridge single-phase inverters and control techniques designed for single-phase inverters still work in the three-phase systems, new control problems emerge after the three phases are combined together in that the reference frame issue and the PWM issue become problems. In this report, control to be performed in synchronous $\alpha\beta 0$ reference frame is suggested together with a new modified space vector PWM scheme. Besides, in this book the common control problems shared by both the three-phase system and the single-phase half-bridge topology will also be addressed by presenting a new control solution with detailed analysis of its performances and robust stability. [23]

C. *Power Control of DG in Grid-Connected Mode*

Power control, including real power P and reactive power Q controls, of a DG inverter in grid-connected mode with existence of local load is of interest. The challenges come from the fact that the system should also be able to supply quality power to the local load in island mode. Based on this fact, control solutions yielding stability, fast transient response, and less coupling between P and Q are desired. It is essential to recognize knowledge about how the utility grid helps the control of a DG unit in transients. There has not been any published work addressing the methodology of obtaining the knowledge of the grid and applying the knowledge in DG control in real time. If the local load of the DG unit is nonlinear (e.g., diode rectifier sort of load), it tends to draw a harmonic current for the feeder. In island mode, the DG unit is the only feeder. However, in grid-connected mode, how the harmonic current is shared by the DG unit and grid becomes a concern. Harmonic free line current is always desired, and how to let the DG unit take all the harmonic current is an important problem. We will adress the power control technique later.

In practice, the voltage of a utility grid often has harmonic distortion. Whether the DG unit can identify the harmonic components in the grid voltage and compensate for them to maintain clean sinusoidal line current becomes a challenge.

In most cases, from the power control point of view, the inverter topology does not matter. [24]

D. *Front-End Rectifier Control in Three-Phase Three-Wire AC–DC–AC Systems*

If a front-end PFC rectifier exists in a three-phase three-wire AC–DC–AC double conversion system, once the inverter load is not balanced, the output power is no longer a constant, which leads to fluctuation of the DC link voltage. On the rectifier side, the ripple corrupted DC link voltage is fed back to the voltage regulator, which generates a fluctuating d-axis current command under a constant DC voltage reference.

If the current regulator of d-axis has high bandwidth, it yields fast current tracking and consequently a fluctuating rectifier output current which causes unbalanced frontend input current in the input current. This situation is undesirable regardless of whether the front end is fed by a power system or a single generator. In this book, the effects of unbalanced inverter load on the DC bus will be analyzed and evaluated. A rectifier control methodology with a method solving this problem will be needed. [25]

V. Conclusion

This paper present distributed generation (DG) architectures different control of converter for utilizing renewable energy sources, such as wind power, solar power, fuel cell (FC) plants, high-speed micro-turbine generator (MTG) plants, and storage devices as local energy sources.

It emphasizes control technology for controlling power converters to supply the loads and to regulate voltage, frequency and power oscillations.

Furthermore, this paper open new vistas for simulation studies and experimental work to address the critical need of industry in expanding the knowledge base in green energy systems, power electronics, and control technology.

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