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A Review of Distributed Control Techniques for Power Quality Improvement in Micro-grids

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Abstract. Micro-grid is typically visualized as a small scale local power supply network dependent on distributed energy resources (DERs) that can operate simultaneously with grid as well as in standalone manner. The distributed generator of a micro-grid system is usually a converter-inverter type topology acting as a non-linear load, and injecting harmonics into the distribution feeder. Hence, the negative effects on power quality by the usage of distributed generation sources and components are clearly witnessed. In this paper, a review of distributed control approaches for power quality improvement is presented which encompasses harmonic compensation, loss mitigation and optimum power sharing in multi-source-load distributed power network. The decentralized subsystems for harmonic compensation and active-reactive power sharing accuracy have been analysed in detail. Results have been validated to be consistent with IEEE standards.

1.Introduction

Distributed generation (DG) has brought up a new paradigm for more flexible, reliable and efficient power systems. It is potentially an internet of power in which all types of power sources are scattered over the distribution network, remotely and in proximity with the loads. DG, apart from all its merits, causes power quality problems with different penetration levels. Imbalance of voltage profile, frequency mismatch, current distortions and inaccurate management of active and reactive power are highly objective. Recent developments in this field have shown an ambiguous relation between the DG and power quality. Some experts argue on the drawbacks of distributed generation installation in inter-connected power networks, others emphasize its restorative effects for power quality improvement. For example, the voltage support at common grid bus is frequently argued. DG can support the grid where voltage support is hardly available or very weak. Conversely, DG units may lead to transient instability, voltage fluctuations, frequency deviations and harmonics.

Generally, every distributed generator performs both on-grid and standalone operations as per load demand, the controller corrects voltage and frequency imbalances in the supply network, power is controlled independently and load requirements of the end users are regularly met. This paper discusses the architecture of DG based micro-grids, their control systems and solution of problems that arise due to their installation or integration. The paper presents a detailed analysis of power quality improvement techniques including harmonic compensation approaches to take care of the major challenges in order to enhance overall efficiency and reliability. After the analysis of conventional methods, advanced approaches for power quality improvement in micro-grids have been discussed with technical merits.

2. Architecture of a Micro-grid System

The concept of micro-grid was proposed by Consortium of Electric Reliability Technology Solutions (CERTS) as a system consisting micro-power resources which can provide electric as well as heat power to the distributed loads. Power electronic devices perform energy conversion and storage, with desired modulation and control. Micro-grid has the capability to operate as a singly controlled element or simultaneously with the main or utility grid, to meet power demand and quality for end utilization. In United States, CERTS's micro-grid concept presents a systematic overview of its architecture, design, control, and operation in regulating, managing and providing power. Robert H. Lasseter, Professor in Engineering at the University of Wisconsin Madison, put forth a fundamental micro-grid structure according to the concept of CERTS, as shown in figure 1. This micro-grid has four micro-sources connected at nodes 8, 11, 16 and 22 [1]. The specific architecture varies with different types of load, communication and control and monitoring technologies. However, a lot of structural variants are based on the distributed nature of the supply network and have high efficiency and reliability.

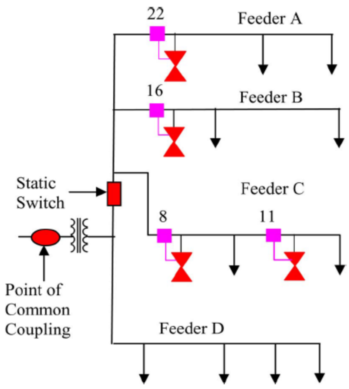

Figure 1. Architecture of CERTS micro-grid [1]

"European Commission Project Micro-grids defines micro-grid as a system that uses power electronic devices for energy regulation to provide users with cold, heat, and electricity; it takes the advantage of micro-power source from the primary energy, which can be divided into uncontrolled, partly controlled and fully controlled types" [2]. It can be concluded from this definition that European Union emphasizes on efficient control of micro-power. There are different types of micro-power sources used within a micro-grid system, typically small generation units with power ratings of < 100kW. Commonly used energy sources are photovoltaic cells, wind turbines, micro-turbines, fuel cells and energy storage devices are batteries, flywheels and super capacitors. These sources are interfaced with the loads and the main grid through power electronics interfaces at the user's side [2]. There are two distinct components of micro-gird control: 1) micro-grid configuration manager, for supervisory control and 2) power flow controller, for controlling DG units. Due to varying load demand, the power flow controller dynamically regulates active and reactive power based on local voltage and frequency information, and the DG units adjust their power output accordingly to maintain power balance and inertia. Information and communication technologies (ICT) at supervisory layer provide an additional degree of monitoring.

3. Distributed Control Techniques for Micro-grids

Micro-grid system has two operating modes: 1) grid-connected mode and 2) islanded mode. Reliability, efficiency, load management and power control are the key features of this type of power generation and supply network. Contrarily, large-scale use of DG units may lead to transients, voltage instability, power fluctuations, and harmonics. "All renewable energy sources are uncontrollable and unstable in nature which leads to output power fluctuations. When micro-grid is connected or disconnected from the main grid it causes the voltage profile to unbalance. When micro-grid is heavily loaded, small voltage drop may lead to partial voltage instability" [3]. As the conventional power systems are being replaced with DG, so the issues linked with micro-grids need to be addressed to effectively improve the quality of delivered power. Potential features associated with power quality are voltage control, frequency regulation and harmonic compensation [4]. Power quality improvement techniques are described in detail in the following sections in terms of power flow and power management.

3.1. Power Flow

There are a couple of control methods [5]-[7] for power source that make the use of power electronic inverter control using voltage/frequency regulation, PQ control method in grid-connected operation with grid power. An effective modular approach is presented with experimental results in [8] to improve micro-grid power quality and power sharing accuracy simultaneously. Recommendation on micro-grid power flow control by CERTS is to ensure: 1) new micro-power sources can be added without damaging the existing systems, 2) the independence of choosing system operating points, 3) the connection to or isolation from grid seamlessly, 4) active and reactive power processing corresponding to load variations [9]. Power flow control can be further classified for different configurations of micro-grid systems.

Voltage and Frequency (V/f) Regulation control mode is a good candidate for islanded (off-grid) operation of micro-grids. In islanded mode of operation, adequate voltage and frequency support can be provided for stability of micro-grid by making use of inverter voltage and frequency regulation. The supervisory control for extra communication infrastructure in not needed, and only local voltage and frequency is used as feedback. This is described in detail in [10] and simulation based analysis is presented in [11]. Active and Reactive Power (P/Q) Control configuration is used mostly in grid-connected mode of operation of micro-grids. In such situation, the main/utility grid controls the micro-grid load power and fluctuations in voltage and frequency to meet load requirements without any contribution of micro-grid for voltage and frequency regulation. The controller in P/Q control mode is designed to operate in cascaded double loop control for feed-forward compensation in DC voltage [12]. The inner and outer loops are for current feedback regulation and active and reactive power decoupling, respectively. To validate the results, its output has been verified using 5MVA feeder and provides with satisfactory power tracking characteristics [13].

3.2. Power Management

Micro-grid is quite different as far as its control is concerned from the previous centralized to distributed and interactively networked type of control. To manage the power during different modes and transitions at any instant, information must be processed at high speed by different control components to trigger the required system response. System economics, security, stability and other aspects can be achieved only through mutual coordination among all levels of distributed control and power processing units. The choice of power management method is also affected by the inter-dependency of micro-grid components, which requires integration effort to select the most suitable method to ensure system security and reliability.

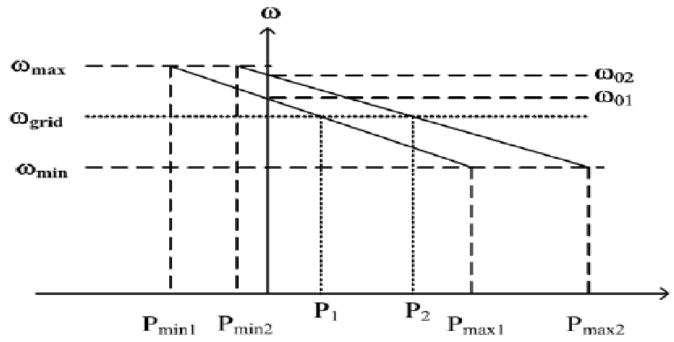

Figure 2. Active power and frequency droop curve [14]

Load Frequency Control; in islanded mode, the micro-grid operation can use two methods to regulate voltage and frequency as a result of load unbalance. One method is to achieve the local secondary control through a controlled DG unit and the other one is micro-grid central control (MGCC). The anticipated value of the reactive power of the prime mover of the two cases can be determined as per frequency deviation [14]. Figure 2 shows characteristics curve determined by the MGCC known as droop curve in isolated mode of micro-grid operation for frequency restoration. This satisfies the criteria of balance of power while importing from or exporting to the grid. Decentralized Control; separate control modules on the active and reactive power are implemented in this method. It also has large impact in adjusting the balance of power and adding the frequency recovery mechanism. Decentralized power control strategies based on the characteristics curves of voltage and frequency, voltage management and reactive power compensation, with recovery strategy and efficient frequency control are described in [15].

4. Advanced Control Techniques for Power Quality Improvement

DG works as power internet with renewable energy resources distributed over the network, providing continuous power using ICT, advance monitoring and sensor networks. In order to cope with these complex systems, advanced power quality control techniques are needed which are analysed as follows.

4.1. Harmonic Mitigation

In the distribution feeders, DG acts like a non-linear load, while the inverters generate higher order harmonics. Sinusoidal PWM or space vector PWM techniques are very helpful in overcoming these issues [16]. The duty cycle of square wave is transformed for controlling output power. It helps in filtering output wave into a pure sinusoidal since less energy is absorbed or released. Harmonic mitigation approaches are based on making the DG units of a distributed power system at harmonic frequencies behave as a resistance. An advanced distributed control strategy has been developed in [17] with power flow management and power sharing functions. This useful, low cost and compact design improves power quality effectively without the need of separate controllers in dq (synchronous) and αβ (stationary) reference frames and additional phase-locked loops (PLL) and provides smooth output voltages and currents in grid-connected and islanded modes of micro-grids. The power flow control functions are given as

$$P = \left[\frac{E\,V}{Z}\cos\phi - \frac{V^2}{Z}\right]\cos\theta + \frac{E\,V}{Z}\sin\phi\sin\theta,\quad Q = \left[\frac{E\,V}{Z}\cos\phi - \frac{V^2}{Z}\right]\sin\theta - \frac{E\,V}{Z}\sin\phi\cos\theta \quad (1)$$

4.2. Voltage Compensation

For both grid-connected and islanded mode of operation, voltage control loop can be used. Proportional Resonant (PR) Controller is used for the implementation of voltage and current control loops [18]. A linear system model is used to analyse the dynamics of closed loop and to measure the required controller gain. A non-linear current flowing through the load causes voltage distortions that appears at the point of common coupling. A capacitive virtual impedance loop can also be used to damp the voltage harmonics at the point of connection with load by introducing a capacitive component and effectively distorting the output voltage of inverter [18]. Hence harmonic voltage is obtained via virtual impedance to the inner loops that provide compensation against drop due to inductive grid side impedance.

4.3. Unbalanced Compensation

To maintain adequate power quality level in islanded mode, an unbalanced compensation technique is proposed using a dump load (DL) consisting IGBT based three 1-φ rectifier bridges and static compensator (STATCOM). "STATCOM is a bidirectional three-phase PWM voltage source inverter, connected in parallel with the micro-grid, ensuring reactive power balance among phases" [18]. Due to varying loads, load frequency control (LFC) technique is implemented. For calculating system frequency and phase, phase locked loop (PLL) circuit is utilized with the additional advantage of STATCOM output voltage synchronization. DL control method uses two control loops, based on PI Controllers. One for frequency; a high speed one and other for active power unbalance; a slow speed one. The difference between measured and rated frequency is fed to the controller for providing active power output that needs to be dissipated by the DL. A redistribution algorithm of three phases confirms active power balancing via slower loop. STATCOM principle measures the average of load reactive currents, targeting the reactive currents to average value. Added features improve harmonic compensation, voltage fluctuations and flicker [19]. Block diagrams of DL and STATCOM controller are shown in figure 3 and 4.

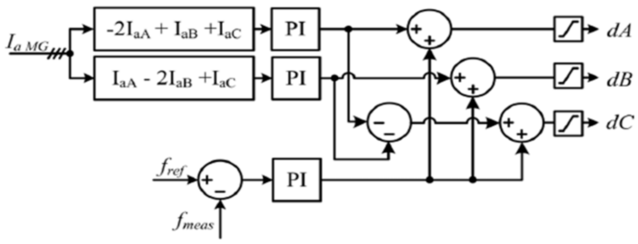

Figure 3. DL Controller [19]

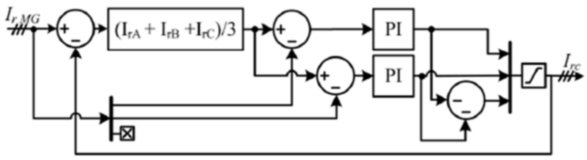

Figure 4. STATCOM Controller [19]

4.4 Droop Control Technique

Droop control technique is employed for power sharing while adjusting frequency and inverter voltage amplitude. In this method, the controller acts as a large power generator, while keeping line impedance inductive. For micro-grids like low voltage network, impedance is mainly resistive. Active power, reactive power, voltage and frequency droop curves can be decoupled by the system voltage and frequency regulation. The inverter can be controlled with two types of configurations. One of them is active power-frequency (*P-ω*) and reactive power-voltage (*Q-V*). Another one is active power-voltage (*P-V*) and reactive power-frequency (*Q-f*). [20] The frequency and magnitude of the voltage is dependent on the voltage source invertor controlled by the droops. The real power becomes higher, by increasing output voltage, whereas reactive power is reduced by increasing power angle. Hence, the real measures of active and reactive power are *P-V* and *Q-ω* droop and boost functions respectively.

4.5 Cyber-Physical System based Control

Cyber-Physical Systems (CPS) involve combination of cyber and physical resources for providing sensing, processing and computational platforms. Under fault situations in grid-connected mode, high voltage spikes and current fluctuation are experienced. The behaviour of micro-grids with main grid in steady state and transient conditions can be modelled as a hybrid system involving both continuous and discrete operating states [21]. DC interface and voltage source inverter are the two major components of micro-source that couples with the power system via inductor. Hence it can determines the flow of real and reactive power from the system. This design involves the turning ON and OFF of main grid along with two micro-sources by using discrete states in different combinations as shown in figure 5 [22]. Eight different operation modes are readily available to be used in supply network.

When the fault is recovered, system goes back to the normal state autonomously. This CPS based strategy ensures efficiency and power quality during continuous and discrete signals transitions.

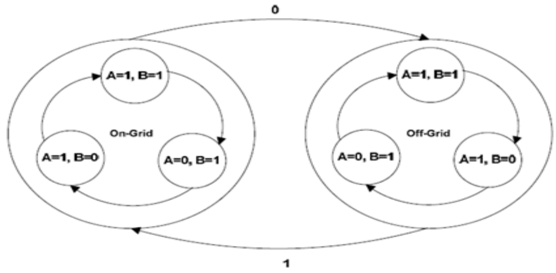

Figure 5. Transitions of micro-power sources in CPS based control [22]

5. Conclusion

The concept of micro-grid has revolutionized the world of power systems with flexibility of power distribution from small to large scale. One of the major aspects for the development in this field is to avoid large power breakdowns as micro-grid can work in isolated mode if the primary supply fails. This can happen using the supervisory or distributed control of energy storage devices for the optimum utilization of energy resources. The analysis of power quality improvement strategies and advanced methods for micro-grid control has been presented. These strategies in all conditions ensure system efficiency, reliability, security and economics under different operating conditions for micro-grids of distributed nature. The overall contribution of this research is to provide strong foundation for developing efficient and reliable distributed control techniques for smart and micro-grids.

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