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Advanced Control Architectures for Intelligent Microgrids – Part II: Power Quality, Energy Storage, and AC/DC MicroGrids

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Abstract— This paper summarizes the main problems and solutions of power quality in Microgrids, distributed energy storage systems, and AC/DC hybrid Microgrids. First, power quality enhancement of grid-interactive Microgrids is presented. Then, cooperative control for enhance voltage harmonics and unbalances in Microgrids is reviewed. After, the use of static synchronous compensator (STATCOM) in grid-connected Microgrids is introduced in order to improve voltage sags/swells and unbalances. Finally, the coordinated control of distributed storage systems and AC/DC hybrid microgrids is explained.

***Index Terms*—Microgrids, distributed energy storage, power quality, STATCOM.**

I. Introduction

A microgrid is a local grid consisting of Distributed Generators (DGs), energy storage systems, and dispersed loads, which may operate in both grid-connected or islanded modes [1], [2]. DGs are often connected to the microgrid through a power electronic interface converter. The main role of an interface converter is to control the power injection. In addition, compensation of power quality problems, such as voltage harmonics can be achieved through proper control strategies [3]. The voltage harmonic compensation approaches are based on making the DG unit to emulate a resistance at harmonic frequencies in order to compensate those harmonics [4]-[10].

Voltage unbalances could appear when connecting single-phase loads to the microgrid. Compensation of voltage unbalances is usually done by using series active power filter through injection of negative sequence voltage in series with the power distribution line [4]. However, there are also works based on using shunt active power filter for voltage unbalance compensation [6]. In these works, voltage unbalances caused by unbalanced loads are compensated by injecting negative sequence currents. In addition, when the voltage is highly unbalanced and distorted, a big amount current is needed, thus DGs must be oversized or this compensation would interfere with the active and reactive power supply by the DG. In such a case, the use of static synchronous compensators (STATCOMs) in microgrids can be well justified.

Furthermore, DC- and AC-microgrids have been proposed for different applications, and hybrid solutions have been developed Microgrids can be conceived to use DC or AC voltage in the local grid [11]. Also, there are AC sources or microgrids interconnected by means of power electronic interfaces to a DC microgrid. Thus hybrid DC-AC microgrids are often implemented, being necessary to control the power flow between DC and AC parts. In this sense, it seems reasonable that the DC-microgrid area can be connected to storage energy systems like batteries, supercapcitors or hydrogen-based fuelcells. Although DC transmission and distribution systems for high voltage applications are well established, and there is a notable increase of DC microgrid projects, we cannot find so many studies about the overall control of these systems.

This paper is summarized as follows. In Section II power quality of microgrids and interactivity with the grid is presented. In Section III cooperative control is applied to microgrids to enhance power quality. Section IV introduces the control of distributed storage systems in microgrids. Section V presents AC and DC microgrids coordinated control. Conclusions and future trends are pointed out in Section VI.

II. Power Quality Enhancement between Utility and Microgrids

Microgrids should preferably tie to the utility grid so that any surplus energy generated within them can be channeled to the

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utility. Similarly, any shortfall can be replenished from the utility, which preferably should only be occasional, since microgrids should mostly be designed as self-sustainable, if frequent load shedding is not intended [12]. Having an inter-tie would also expose the microgrids and utility grid to their respective inner disturbances, like harmonics, unbalance and other power quality "noises". To better isolate the grids from their respective "noises", a power quality conditioner is recommended between each microgrid and the utility grid, as demonstrated in Fig. 1. This power conditioner should ideally have a shunt converter and a series converter, in order to achieve full voltage and current compensation. Indeed, such configuration would appear similar to a unified power quality conditioner (UPQC) [13]-[15] or a unified power flow controller (UPFC) [16], which certainly is the case when judging on their power stages. Their control schemes are however different, as can be seen when comparing the requirements of a microgrid power quality conditioner (MPQC) with those of an example UPQC.

For the former, there is a general incline towards controlling the shunt converter to provide a regulated voltage within the microgrid, whose parameters are properly tuned for power dispatch or sharing purposes [17], [18]. A firm voltage would definitely help with the interfacing of other localized sources, and the avoidance of sensitive load tripping within the microgrid. This is especially important in the islanded mode, during which the utility grid is not available for stabilizing the network voltage. A firm voltage imposed by the shunt converter would however cause large unbalanced current to flow along the interconnecting feeder, if the utility voltage is unbalanced, and the series converter is not in operation. The problem would prevail even for a small amount of unbalanced voltage, because the feeder impedance is usually small. Harmonic voltages, if present in the utility grid, would likewise lead to harmonic currents along the feeder. They however are of a lesser concern, since their values progressively contract, as the feeder impedance increases with harmonic order.

To nonetheless remove these non-idealities from the current, one probably obvious method is to control the series converter to inject voltages that correspond directly to the unbalanced and harmonic voltages detected in the utility grid. None of the distorted and unbalanced voltages now appears across the feeder, inferring that no corresponding current components will flow. The main difficulty encountered here would be the impossibility of detecting the non-idealities in the utility grid, which is usually far away. Indirect determination is therefore needed, and can be done by first filtering out the line current

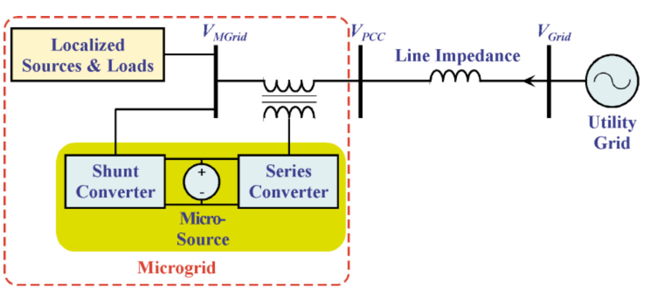

Fig. 1. Illustration of network with distributed sources and storages.

non-idealities using notch filters or filters in the relevant synchronous frames [19]. These current components can then be forced to zero by passing them through controllers with large gains, ideally infinite, at the frequencies of interest. The outputs of the controllers would then ensure that the series converter injects the right amount of unbalanced and harmonic voltages, so that the feeder carries only balanced sinusoidal current, which also flows through the series converter. Noting further that the series converter produces only unbalanced and harmonic voltages, while carrying only positive-sequence balanced current, its active and reactive powers injected to the grid are zero.

The same principles would apply during utility voltage sag, during which the feeder current will again be large. To reduce this current, the series converter can be controlled to introduce a large impedance along the feeder, so that the large voltage difference caused by the sag appears mostly across it, and not the feeder. Current flow through the feeder is then reduced accordingly. The main concerns here would be to sense the instants of sag initiation and recovery, but cannot be done by measuring the grid voltage, which is usually faraway, and therefore not readily accessible. The former can however be detected by sensing the initial current surge along the feeder, while the latter can be detected by sensing the voltage at the point of common coupling (PCC), which would roughly be equal to the grid voltage during the sag [15], [16].

For convenience of referencing, the main requirements discussed above for MPQC can neatly be summarized as:

- Controlling its shunt converter in voltage mode, so as to produce a well regulated voltage in the microgrid.
- Controlling its series converter in current mode, so as to produce balanced sinusoidal line current.
- Controlling its series converter as a large impedance for limiting the line current during utility voltage sag.

These requirements can be realized by various basic voltage and control-mode control schemes with any number of inner control loops. Regardless of the final implementation adopted, the control objectives here are undeniably different from those of UPQC, listed as follows [11]-[13]:

- Controlling its shunt converter in current mode, so as to shape the grid current as balanced sinusoid (unbalanced and harmonic load current compensation).
- Controlling its series converter in voltage mode, so as to balance the load terminal voltage (unbalanced and harmonic grid voltage compensation).
- Controlling its series converter in voltage mode, so as to improve the downstream load voltage quality during upstream utility voltage sag (series voltage injection).

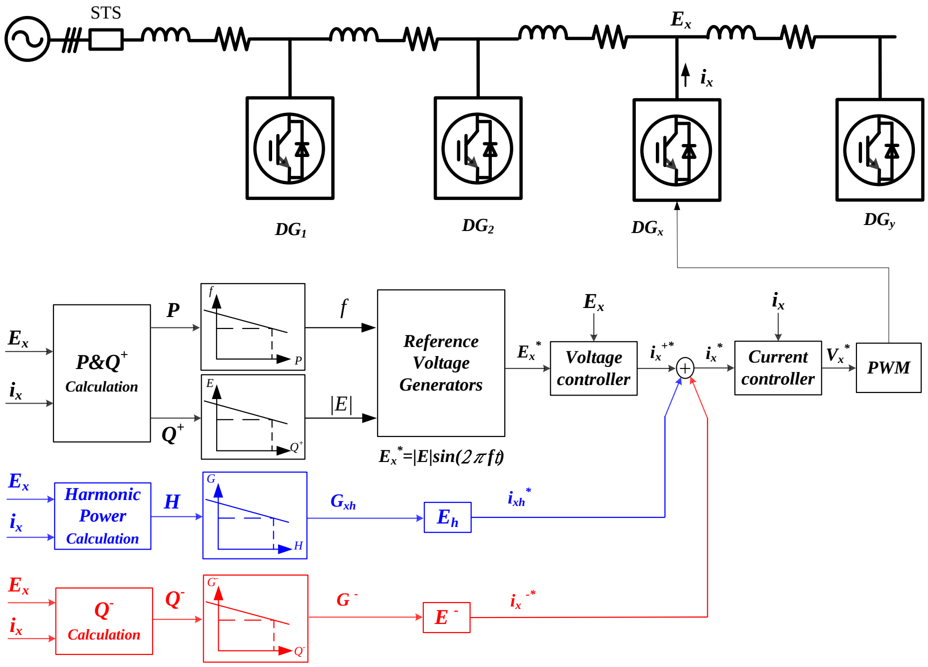

Fig. 2. Control algorithms of cooperative voltage harmonic and unbalance compensation.

III. Cooperative Control for Power Quality Enhancement in Microgrids

Deep penetration of renewable energy sources (RESs) leads to severe voltage distortion and voltage fluctuation [20]. Various international standards have included limitations of power quality to assure proper operation of microgrids [21]. In the grid-connected operation, the utility needs to balance power flow between sources and loads, and to maintain voltage quality. In contrast, inverter-based DGs must coordinate power requirements in the islanding networks. In order to maintain decent power quality as well as collect more energy from RESs, power conditioning equipment is definitely required, for example active power filters and STATCOMs [22]-[24]. Here, we will exclusively focus on cooperative solutions to voltage quality in the islanding microgrids, followed by the STATCOM to suppress voltage fluctuation in the grid-connected operation.

A. Distributed compensation

Compared with the grid-connected mode, voltage distortion and voltage unbalance in islanding networks are severe due to high line impedance and uneven distribution of single-phase DGs/loads [25], [26]. Instead of installing power conditioning equipment, a preferable solution is to provide power-quality services by inverter-based DGs. That means, in addition to transferring fundamental power, the inverter needs to provide harmonic filtering as well as unbalanced suppression. In order for multiple DGs to work cooperatively, a coordinating or supervisory algorithm is definitely needed, for example the droop control and low-bandwidth communication systems [27], [28]. Here, we will review various cooperative compensations developed for distributed DGs.

In [29], Tuladhar *et Al.* presented a harmonic power vs. voltage loop bandwidth droop to share the harmonic current among multiple inverters when sharing nonlinear loads. However, since this approach is based on increasing the gain of the voltage loop to reduce the bandwidth when the distortion increases, it can affect to the closed-loop system stability. In addition, high frequency signals with small magnitude are generated and injected by the converter over the voltage waveform. Then, the response is sensed back in order to achieve good reactive power sharing in spite of the asymmetrical power lines. Thus, high PWM frequency with fine resolution is required to successfully implement this control algorithm.

In [30], Borup *et Al.* proposed a virtual inductor that operates at certain harmonic frequencies, in order to share between the inverters the harmonic current produced by nonlinear loads. This method would be effective as the converters are installed at the same location. Voltage detection active filters with droop-controlled harmonic conductance were presented to reduce voltage distortion in the power system [31].

In order to cooperatively compensate voltage harmonics by using multiple DGs, a power-harmonic conductance droop ($H - G_h$ droop) was proposed in [32]. This way the harmonic conductance command value G_{xh} can be obtained and multiplied by the harmonic distortion E_{xh}, hence generating the harmonic current reference i_{xh}^{*} as follows:

$$i_{xh}^{*} = G_{xh} \cdot E_{xh} \tag{1}$$

This harmonic current reference is added to the fundamental current reference, which is often generated by the voltage control loop.

Fig. 2 shows the control block diagram of the cooperative compensation controller. The designed $H - G_h$ droop (blue line) can be integrated together with the active power vs. frequency droop ($P - f$) and the positive-sequence reactive power vs. voltage ($Q^{+} - E$) droop. Notice that only Q^{+} is used to adjust the voltage amplitude, since the negative-sequence reactive power Q- will be used for unbalance voltage compensation. The H – G_h droop equation for DG_x is defined by

$$G_x = G_0 - b_x \cdot (H_{x0} - H_x) \quad (2)$$

where b_x is the droop coefficient, H_{0x} is the rated harmonic power, and G_0 is the rated conductance. If the droop coefficient is designed in inverse proportion to the rated harmonic power, the total harmonic power will be evenly shared among DGs in proportion to their rated capacity:

$$b_1 H_{10} = b_2 H_{20} = \cdots = b_x H_{x0} = b_y H_{y0} = b_z H_{z0}$$
$$\frac{H_1}{H_{10}} = \frac{H_2}{H_{20}} = \cdots = \frac{H_x}{H_{x0}} = \frac{H_y}{H_{y0}} = \frac{H_z}{H_{z0}} \quad (3)$$

Accordingly, multiple DGs can cooperatively without using communications can share the harmonic current injected to reduce the harmonic voltage. This approach is suitable for microgrid DGs supplying nonlinear loads.

On the other hand, a shunt or series converter could be controlled to inject negative-sequence current in order to reduce unbalanced voltage [33], [34]. As can be seen from Fig. 2, the negative-sequence conductance G_x^- was introduced in the DGs control for this purpose [34]. Thus, the negative-sequence current can be expressed as follows:

$$i_x^- = G_x^- \cdot E_x^- \quad (4)$$

where G_x^- is the conductance (proportional gain) that regulates the amount of negative-sequence current (i_x^-) to be injected tp compensate the amount of negative-sequence voltage (E_x^-).

Additionally, a Q^- – G^- droop (red line) was established based on the negative-sequence reactive power Q_x^- with respect to the negative-sequence conductance G_x^- in order to allow DGs to cooperatively share the unbalance compensation, i.e. share the amount of Q^- to be injected to the reduce E^-.

The definition of the Q^- – G^- droop equation is given as follows:

$$G_x^- = G_0^- - u_x \cdot (Q_{x0}^- - Q_x^-) \quad (5)$$

where u_x is the Q^- – G^- droop coefficient.

Notice that if E^- increases due to the voltage unbalance, Q^- will be naturally increased. In this situation, the Q^- – G^- droop will increase G^-, and the amount of i_x^- will increase accordingly, thus decreasing E^-, which is the main control objective. That means that all the DGs will reach a steady-state point, and they can share the amount of Q^- according to the u_x selection. Consequently, Q^- could be evenly distributed among DGs based on each DG rated power capacity, bearing in mind that the droop coefficient u_x is inversely proportional to the rated power of DG_x, according to:

$$u_1 Q_{10}^- = u_2 Q_{20}^- = \cdots = u_x Q_{x0}^- = u_y Q_{y0}^- = u_z Q_{z0}^-$$
$$\frac{Q_1^-}{Q_{10}^-} = \frac{Q_2^-}{Q_{20}^-} = \cdots = \frac{Q_x^-}{Q_{x0}^-} = \frac{Q_y^-}{Q_{y0}^-} = \frac{Q_z^-}{Q_{z0}^-} \quad (6)$$

B. STATCOM for Microgrid applications

Voltage regulation in the distributed power system is conventionally realized by using on-load tap changer (OLTC), static VAR compensator, step voltage regulator or switched capacitor [35], [36]. In contrast, STATCOM could flexibly compensate reactive power and also its response time is superior to the other methods. Recent applications of STATCOM to improve power quality in microgrids have been presented recently in the literature [37]-[40].

In [37], Fujita *et Al.* presented an active power filter to suppress voltage distortion and fluctuations. This work illustrated voltage swell, due to DGs, could be mitigated by drawing lagging fundamental current from the grid. The use of a STATCOM to restore positive-sequence voltage and to reduce voltage unbalance has received much attention [38]-[40]. In [40], a STATCOM operating with a positive-sequence admittance and a negative-sequence conductance was proposed. Thus, the reference current i^* can be expressed as:

$$i^* = Y_p^* \cdot E_f^{+'} + G_n^* \cdot E_f^- \quad (7)$$

being Y_P^* the positive sequence conductance, G_n^* the negative-sequence admittance, and $E^+_f{}'$ and E^-_f the quadrature positive-sequence and negative-sequence fundamental voltages.

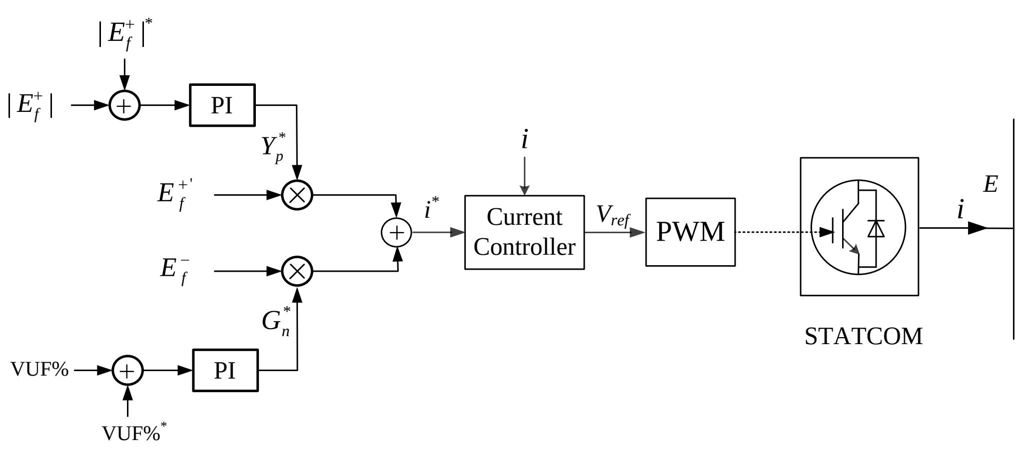

Fig. 3. STATCOM positive-sequence conductance and negative-sequence control diagram.

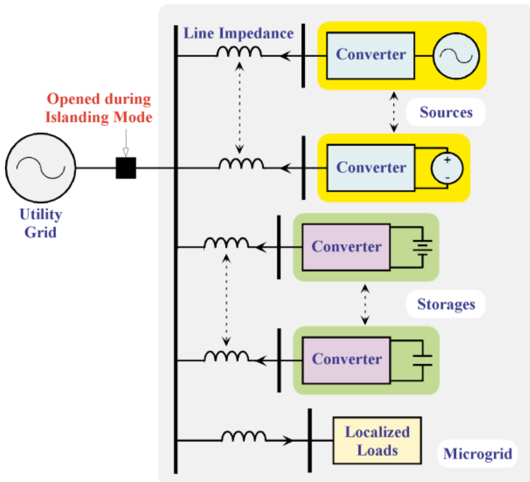

Fig. 4. Illustration of network with distributed sources and storages.

IV. Autonomous Control of Distributed Storages in Microgrids

Most discussions on microgrids or related topics have focused on source power sharing without much consideration about distributed storages, and are therefore not yet rightfully autonomous. Certainly, storages can be found within each source with their combination usually treated as a single entity with smoother power flow [41], [42]. Such arrangement might not be the best option at times, since the storages would occupy prime spaces that can otherwise be used for energy generation. An example is solar generation, where vast amount of spaces is needed for installing photovoltaic panels. In the defense industry, it is also sensible to locate the storages at more secure places, rather than place them near to the exposed solar generators. The idea of distributed storages (DSs) that are distanced from the sources might therefore be an attractive alternative for consideration, like drawn in Fig. 4.

In principles, DSs can be controlled like sources based on the same active and reactive droop characteristics reviewed in Section II [43], [44]. That means their terminal voltages and currents should be measured for calculating the active and reactive powers drawn from them by the loads. These power values are fed to their appropriate droop characteristics to determine the reference voltage magnitude and frequency to be tracked by a classical double-loop control scheme with an outer voltage and an inner current loop. The controlled DSs therefore appear as voltage sources with their power flows not internally defined, but decided by the external loads. That certainly is fine, but would not be satisfactory, if the general purposes of the DSs are to provide energy for smoothening any detected source or load changes, and ride-through enhancement to the overall microgrids [45].

For these functions, the DSs must autonomously sense for the existing system conditions, and request for maximum charging energy only when excess generation capacity is available [45]. As generation capacity drops or demand increases, energy drawn by the storages should decrease spontaneously, until full source capacity is near. At which point, the storages release their stored energy for meeting the extra load demand. A droop characteristic that will meet the above charging and discharging patterns is shown in Fig. 5 with its expressions for realization written as:

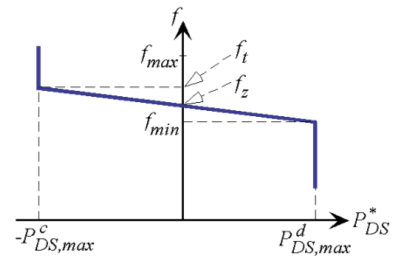

Fig. 5. DS control using frequency versus active power.

$$P^*_{DS} = \begin{cases} -P^c_{DS,max}, & f \geq f_t \\ \gamma'(f - f_z), & f_{min} \leq f < f_t \\ P^d_{DS,max}, & f < f_{min} \end{cases}$$
$$\gamma' = \frac{P^c_{DS,max} + P^d_{DS,max}}{f_{min} - f_t}$$
$$f_z = \frac{P^c_{DS,max} f_{min} + P^d_{DS,max} f_t}{P^c_{DS,max} + P^d_{DS,max}} \quad (8)$$

where γ' is the droop coefficient, f_t and f_z are the frequencies at which charging first decreases and falls to zero, f_{max} and f_{min} are the maximum and minimum frequencies permitted in the microgrid for realizing source droop power sharing, P^*_{DS}, $P^c_{DS,max}$ and $P^d_{DS,max}$ are the active power reference, maximum charging and discharging powers permitted by each DS.

Fig. 5 clearly shows the DS droop having both positive discharging and negative charging active power values. At any instant, the appropriate power to track is determined by sensing the network frequency, which in effect, represents the excess generation capacity of the network. Upon tracked, the DSs will share the charging and discharging active power based on their ratings, as explained in [45].

Works on DS control are quite recent, and areas of possible extension are plentiful like to incorporate them to the hierarchical structure reviewed in Section IV. Further, using of different source characteristics to the control structure is also an interesting issue that needs further exploration.

V. Coordinated Control of AC and DC Microgrids

Traditional utility grids have always been ac due to its relative ease of transmission, distribution, protection and transformation. This preference for ac networks has to a great extent migrated to microgrid development, but the incentives for a full ac microgrid might not be as strong now. Some obvious reasons are the lower power level found in a microgrid, shorter distance of distribution, and a higher portion of sources and storages that are dc by nature. The main contributing dc sources would undeniably be solar energy and fuel cells, and for storages, it would be different types of batteries and capacitive storage mediums. Like for an ac microgrid, the thought of grouping these dc entities together to form a dc microgrid for powering localized dc (mostly electronic) loads

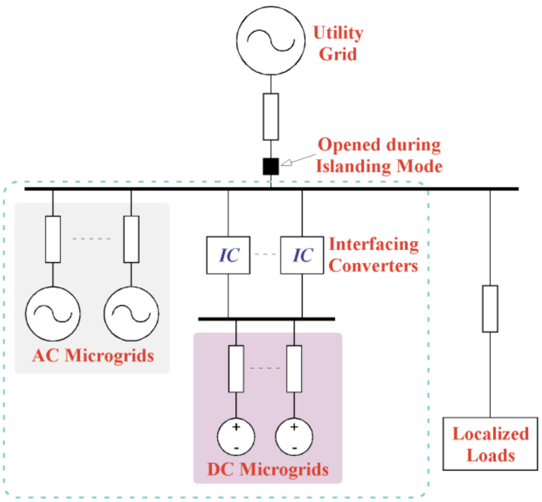

Fig. 6. Example layout of ac and dc microgrids tied by interfacing converter.

might equally be feasible with a significant reduction in power conversion stages expected [46]. Co-existence of an ac and a dc microgrid with an interfacing converter, like in Fig. 6, is therefore likely, inferring that methods for coordinating them should be discussed.

Probably, the simplest approach is to treat each microgrid as an independent network with either dc sources supplying only dc loads, or ac sources supplying ac loads. That certainly defeats the purpose of linking the two microgrids, and would require much higher source ratings, in order to always meet supply and demand within each microgrid. To better coordinate the microgrids, and hence lowering the source ratings, some forms of energy sharing between them must be introduced with preferably no or only slow communication link [7]. That would certainly require some means of droop control, where Section II has already reviewed, but more for sharing power among the sources in the ac microgrid. Extension to the dc microgrid is possible, and would simply involve replacing the active power vs. frequency droop ($P - f$) droop for the ac microgrid by the acive power vs. dc voltage droop ($P - V_{dc}$) for the dc microgrid [47]. Upon implemented, power sharing among sources in the dc microgrid would be realized with some minor errors expected. This slight sharing inaccuracy is no different from that experienced by reactive power sharing in the ac microgrid, as discussed in Section II.

The next concern is to introduce power sharing between the ac and dc microgrids, treated as two separate entities. Droop representation of each entity can rightfully be determined by summing the individual source characteristics in each microgrid, leading to an overall P–f droop for the ac microgrid and an overall P–V_{dc} droop for the dc microgrid. Information from these two droop characteristics should properly be merged, before using it to decide on the amount of power to transfer across the interfacing converter. For that, the recommendation written in the following equation is to normalize the frequency in the ac microgrid and voltage in the dc microgrid, so that their respective ranges of variation commonly span from −1 to 1 [67]:

$$f_{pu} = \frac{f - 0.5(f_{max} + f_{min})}{0.5(f_{max} - f_{min})}$$
$$V_{dc,pu} = \frac{V_{dc} - 0.5(V_{dc,max} + V_{dc,min})}{0.5(V_{dc,max} - V_{dc,min})} \quad (9)$$

where subscripts *max* and *min* represent the respective maximum and minimum limits of f and V_{dc}, and subscript *pu* represents their normalized per-unit values. These normalized variables should next be forced equal by feeding their error to a PI controller, followed by an inner current controller [49]. Upon equalized, the two microgrids would share active power based on their respective overall ratings [48]. This thought is no different from enforcing a common frequency in the popularly discussed ac microgrid, upon which the ac sources would share power proportionally based on their respective ratings.

One simple method to keep f_{pu} and $V_{dc,pu}$ equal is to feed their error ($f_{pu} - V_{dc,pu}$) to a PI controller, whose output is the active power reference P_{Ik}^* that must be transferred from the dc to ac microgrid through the interfacing converter when positive, and vice versus. The determined P_{Ik}^*, upon converted to a current command, can be tracked by any forms of closed-loop current control ranging from classical PI control in the synchronous frame, state feedback control and repetitive control, to name only a few [48]. The commanded current can also include a reactive component for the ac microgrid, whose value is determined by first measuring the ac terminal voltage of the interfacing converter. The sensed voltage value, upon passed through the same reactive droop characteristic discussed in Section II, would give the reactive power and hence reactive current references that the interfacing converter should inject.

Certainly, the power sharing principle reviewed here is only a possible method of control. Other management principles with different objectives could be defined for future investigation.

VI. Conclusions and Future Trends

Voltage unbalance and harmonic compensation control strategies for microgrids have been reviewed. In islanding operation, the $Q^- - G^-$ droop (unbalanced reactive power vs. negative-sequence conductance) the $H - G_h$ droop (harmonic power vs. harmonic conductance) were described. These control lops can be implemented together with $P - f$ and $Q - E$ droops, so that multiple interface converters of DGs can cooperatively share all workloads in distorted and/or unbalanced networks. On the other hand, voltage regulation of grid-connected microgrid can be accomplished by STATCOM, so as to allow more DGs operating on-line with an acceptable level of voltage rise.

A power quality conditioner with a shunt and a series inverter has been presented for interfacing microgrids to the utility grid. The shunt inverter is responsible for keeping a set of balanced, distortion-free voltages within the micro-grid, while the series inverter is controlled to inject unbalanced voltages in series along the feeder to balance the line currents with no real and reactive power generated. During utility voltage sags, the series inverter can also be controlled to limit the flow of large fault currents. Collectively, the conditioner has already been shown to raise the quality of power within the micro-grid, and the quality of currents flowing between the micro-grid and utility.

A control scheme for coordinating DSs in microgrids, where DGs and localized loads, was reviewed. An alternative set of droop characteristics and technique for determining control references, that are different from those of DGs, are formulated for DS control. Earlier results have already verified that the presented DS control can autonomously sense for excess generation capacity or supply-demand unbalance, before deciding on the appropriate amount and direction of active power flow.

Further, a control scheme for regulating power flows in a hybrid ac-dc microgrid interlinked by power converters was explained. Through proper sensing of the network information from localized quantities and normalization, results show that the converters are capable of enforcing rated proportional active power sharing among all sources. This sharing is achieved with no dependence on the source natures (ac or dc) and their physical placements within the hybrid microgrid.

Future work is also expected in terms of cooperative control for power quality enhancement in microgrids, for instance in the area of electrical vehicles. In these applications, huge charging current of electrical vehicle may deteriorate power quality. In this case, cooperative control can be integrated into the vehicle charger to assist improving voltage fluctuations and voltage harmonics in the low-voltage distributed system.

Another important issue is that PV or WT power converters, could used additional capacity power rating not only to inject or absorb reactive power, but also to improve the power quality in microgrids.

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