HIERARCHICAL CONTROL OF RENEWABLE ENERGY BASED MICRO GRID

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Abstract—Renewable and distributed energy resources as well as distributed energy-storage systems can be integrated by AC and DC Micro grids (MGs) which are the basic key elements. In the last few years, research work toward the standardization of these MGs has been done. This paper primarily focused on the hierarchical control de-rived from ISA-95 and electrical dispatching standards to develop flexibility and smartness to MGs. The pro- posed hierarchical control consists of three levels:
1) The primary control works base on the droop method, with an output-impedance virtual loop;
2) The restoration of the deviations developed due to primary control are minimized by using secondary control;
3) The tertiary control manages imports or exports the power flow between the MG and the external electrical distribution system.

Keywords— Micro grid, PV system, Island mode, Smart grid, VSI Inverter, Hierarchical control.

I. INTRODUCTION

The significance of electric energy is never ending; Water and Energy are the keys to present life and provide the basis essential for continued economic development increasing energy prices, declining energy availability and safety, and rising environmental concerns are rapidly changing the global energy view. Due to a mounting world population and rising modernization, during the first half of the twenty-first century global energy requirement is projected to more than double and by the end of the century its more than triple. Currently, the world's population is nearly 7 billion, and projections are for a global population approaching 10 billion by mid-century. By introducing alternative fuels upcoming energy demands can meet**.** **I**mprovements in existing energy networks will be insufficient to meet this mounting energy demand. Due to declining reserves and growing concerns over the impact of burning carbon fuels on global climate change, fossil fuel sources cannot be oppressed as in the past [1]. At present centuary securing sustainable and future energy supplies is the greatest challenge faced by all societies [1].
Finding clean and sustainable energy supplies for the future is the global society's most frightening challenge for the twenty-first century. The future will be a mix up of energy technologies with renewable sources such as wind, biomass and solar playing significant role in the new global energy economy. If sustainable energy challenge is not met quickly in the twenty-first century, most of the less-developed countries will suffer major famines and social instability from rising energy prices. Eventually, the world's economic order is at risk. Approximately half of the people living in rural regions live without access to safe and clean water and one-third of the world's population lives in rural regions without access to the electric grid. Solar energy is exclusive source in that. Today With minimal infrastructure requirements we can get electricity and purified water from solar. [1]
This paper mainly focuses on the design and control of the PV system based on cascaded multilevel inverter. The thesis will be consisting of five chapters, which will be organized as follows.

II. MICRO GRIDS

Micro grid is a group of micro-resources or distributed generators, energy storage devices and loads which operate as a single and self-governing controllable system capable of providing both power and heat to the area of service [19]. Micro-grids comprise of small units, less than 100 kW provided with power electronics (PE) interface. Most common resources are Fuel Cell (FC), Solar Photovoltaic (PV), or micro turbines. Desired power quality and energy output is maintained independently during operation by using PE interface and controls of the micro resources. Hence micro grid is termed as a single controllable unit capable of meeting local energy needs with reliability and security.
A micro grid is key component of smart grid which helps to improve system efficiency and reliability. As defined by the Micro grid Exchange Group (MEG), "A micro grid is a set of interconnected loads and distributed energy resources within defined electrical boundaries that acts as a single controllable entity with respect to the grid. A micro grid can connect and disconnect from the grid to operate in both grid-connected or island-mode." [4]

III. REVIEW OF POWER CONVERSION STRUCTURES OF PV SYSTEM

DC is the power generated by the PV panel, and the magnitude is affected by the working conditions. Suitable power conversions needed to be done to

obtain high power quality before delivery for the customer use. Various architectures for PV system have been proposed, and based on their structural arrangement classification have been done as shown in Fig. 1.
Entire Architecture divided into four categories: (a) centralized structure; (b) string structure; (c) multi-string structure; (d) micro-inverter (AC module) structure [14][17][18].

a) ***Centralized Inverters***
This Technology is the most used and conventional structure, as illustrated in Fig. 1(a). Centralized inverters are the base for it which interfaces a large number of PV panels to the grid [19]. The panels are connected in series to form a string arrangement. Strings are connected in parallel, through string diodes, to reach high power levels.

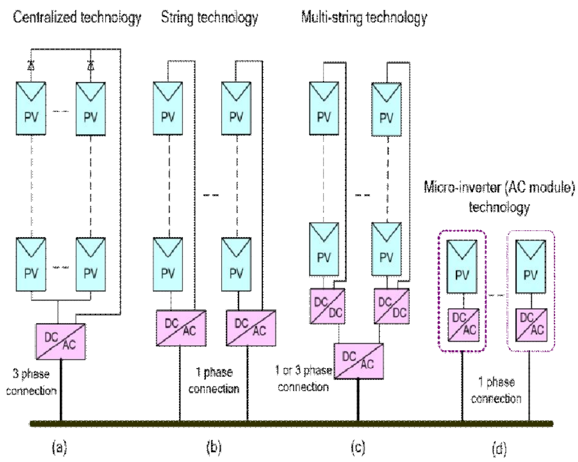

Fig.1. Historical overview of PV system structures: (a) Centralized structure; (b) String structure; (c) Multi-string structure; (d) micro-inverter (AC module) structure.

b) ***String Inverters***
For commercial and residential level PV applications string inverters have been preferred as shown in Fig. 1(b). The string inverter is a compact version of the centralized inverter, where a single string of PV panels is connected to the inverter [22]. String inverters prevent mismatch losses between strings and each string operate at its maximum power point.

c) ***Multi-String Inverters***
The multi-string inverter shown in Fig. 1(c) is the advanced development of the string inverter, where several strings are interfaced with their own dc/dc converter to a common dc/ac inverter [23]. Here every string can be controlled individually that is advantageous. The dc/dc converter is also used to raise PV string voltage to a high voltage dc bus.

d) ***Micro Inverters***
It is also named as AC module inverter due to integration of PV panel and inverter depicted in Fig. 1(d) [24]. It eliminates the mismatch losses between PV panels as only one PV panel is controlled.

A. Grid Connection Requirements
Several standards have been developed for dealing with the different issues involved in the interaction between the distributed generation and utility systems. These standards have been developed by international organizations such as the IEEE (Institute of Electrical and Electronics Engineers) and IEC (International Electro technical Commission), and institutions and utilities local to individual According to these standards, the following are the standards: 1) power quality requirement, 2) fault detection and protection, and 3) synchronization and reconnection. IEC61727 is the standard used in this work.

IV. PROPOSED SYSTEM

The concept has been developed to survive with the penetration of renewable-energy systems, which can be practical if the final user is able to generate, store, control, and manage part of the energy. Based on application point of view DC and ac MGs have been proposed [1]–[12]. The interface between the prime movers and the MGs are power electronic converters acting as voltage sources (voltage-source inverters (VSI) in case of ac MGs. These power-electronic converters are connected across the MG. The droop-control method is applied to avoid circulating currents among the converters without using any l communication between them. The droop method consists of subtracting proportional parts of the output active and reactive powers from the frequency and amplitude of each module to follow virtual inertias. These control loops, also called $P - \omega$ and $Q - E$ droops, have been applied to connect inverters in parallel in uninterruptible power supply (UPS) systems to avoid mutual control wires while obtaining good power sharing. It has several drawbacks that limit its application.

A. Hierarchical Control of AC Mgs
AC MGs are now in the progressive stage of the art [20]–[25]. MGs for standalone and grid-connected applications have been considered in the past as separate approaches. Present days, it is necessary to consider flexible MGs that are able to operate in both grid-connected and islanded modes. This is a great challenge due to the need of integrating different technologies of power electronics, telecommunications, generation, and energy-storage systems, among others.

a) Inner Control Loops
The use of intelligent power interfaces between the electrical generation sources and the MG is compulsory. These interfaces consisting of dc/ac inverters, which can be classified as current-source inverters (CSIs), which consist of an inner current loop and a phase-locked loop (PLL) to continuously

stay synchronized with the grid, and VSIs, consisting of an inner current loop and an external voltage loop. In order to add current to the grid, CSIs are commonly used, while in island or autonomous operation, VSIs are used to keep the voltage stable.

b) *Primary Control*

The main thought of this control level is to imitate the behaviour of a synchronous generator, which reduces the frequency when the active power increases [30]. This principle can be integrated in VSIs by using the familiar P/Q droop method [31] with ω and E being the frequency and amplitude of the output voltage reference, ω^* and E^* being their references,

$$\omega = \omega^* - G_P(s)\bullet(P-P^*) \quad (1)$$

$$E = E^* - G_Q(s)\bullet(Q-Q^*) \quad (2)$$

P and Q are the active and reactive powers, P^* and Q^* as their references, and $G_P(s)$ and $G_Q(s)$ as their corresponding transfer functions (typically proportional droop terms as shown in Fig. 2, i.e., ($G_P(s) = $ m , and $G_Q(s) = $ n).

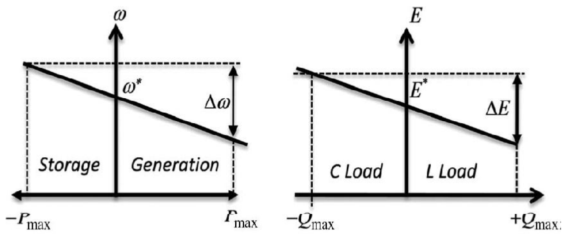

Fig. 2. P/Q droop functions.

Different control-synthesis techniques have been used for the design of $G_P(s)$ and $G_Q(s)$ compensators. Though, the dc gain of such compensators (named m and n) provides for the static ΔP/Δω and ΔQ/ΔV deviations, which are essential to remain the system synchronized and within the voltage-stability limits. Those parameters can be designed as follows:

$$m = \Delta\omega / P_{\max} \quad (3)$$

$$n = \Delta V / 2Q_{\max} \quad (4)$$

With $\Delta\omega$ and ΔV being the maximum frequency and voltage allowed and $P_{\max}$ and $Q_{\max}$ are the maximum active and reactive power delivered by the inverter. If the inverter can absorb active power, since it is able to charge batteries like a line-interactive UPS, then $m = \Delta\omega / 2P_{\max}$.

The frequency-droop function can be expressed as

$$\omega = \omega^* - \frac{m}{\alpha}\cdot(P-P^*) \quad (5)$$

According to Park's transformation the control droops (1), (2) can be modified determined by the impedance angle θ

$$\omega = \omega^* - G_P(s)[(P-P^*)\sin\theta - (Q-Q^*)\cos\theta \quad (6)$$

$$E = E^* - G_Q(s)[(P-P^*)\cos\theta + (Q-Q^*)\sin\theta] \quad (7)$$

The primary-control level include the virtual output impedance loop in which the output voltage can be expressed as [17]

$$v_0^* = v_{ref} - Z_D(s)\cdot i_0 \quad (8)$$

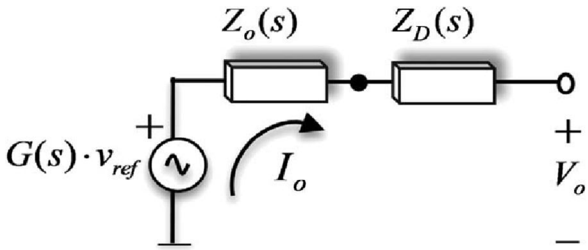

Fig.3. Equivalent circuit of an inverter with the output-impedance loop.

Where v_{ref} is the reference voltage generated by (6) and (7) with $v_{ref} = E\sin(\omega t)$, $Z_D(s)$ is the virtual output-impedance transfer function. The Thévenin equivalent circuit of an inverter with the virtual impedance [47] shown in Fig 3.

The virtual impedance can be expressed as follows:

$$Z_D(s) = L_D\frac{2K_1 s^2}{s^2 + 2\xi\omega_1 s + \omega_1^2} + \sum_{\substack{i=1\\odd}} R_i\frac{2K_i s}{s^2 + 2\xi\omega_0 s + \omega_0^2} \quad (9)$$

Where L_D and R_i are the inductive and resistive impedance values, respectively. K_i is the coefficient of the filter for every harmonic i term.

c) *Secondary control*

Secondary control is proposed to compensate the frequency and amplitude deviations. The secondary control ensures that the frequency and voltage deviations are regulated toward zero after every change of load or generation inside the MG.

It is defined as.

$$\delta p = -\beta\cdot G - \frac{1}{T}\int G dt \quad (10)$$

Where δP = output set point of the secondary controller,

β = the gain of the proportional controller,

$T_{r=}$ the time constant of the secondary controller, and

G is the area control error (ACE), which is usually calculated in about 5-s to 10-s intervals by computers in the

$$G = P_{meas} - P_{sched} + K_{ri}(f_{meas} - f_0) \quad (11)$$

Where P_{meas} the sum of the instantaneous measured active power is transferred at the PCC, P_{prog} is the resulting exchange program, K_{ri} is the proportional factor of the control area set on the secondary controller, and $(f_{meas} - f_0)$ is the difference between the set-point frequency and instantaneous measured system frequency.

The relation between G_ω and G_E shown in Fig.4 for ac MG can be obtained similarly as follows [14]:

$$\delta\omega = k_{p\omega}(\omega_{MG}^* - \omega_{MG}) + k_{i\omega}\int(\omega_{MG}^* - \omega_{MG})dt + \Delta\omega_s \quad (12)$$

$$\delta E = k_{pE}(E_{MG}^* - E_{MG}) + k_{iE}\int(E_{MG}^* - E_{MG})dt \quad (13)$$

Where $k_{p\omega}$, k_{pE}, $k_{i\omega}$, , and k_{iE} are the secondary-control compensator control parameters and $\Delta\omega_s$ is a synchronization term which remains and is equal to zero when the grid is not present. We have to measure the frequency and voltage of the grid to connect the MG to the grid, and that will be the reference of the secondary control loop shown in Fig. 4(a), which can be seen as a conventional PLL.

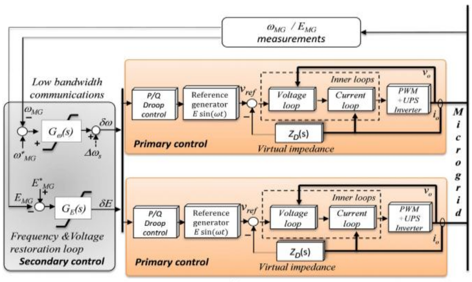

Fig. 4(a). Primary and secondary controls of an ac MG

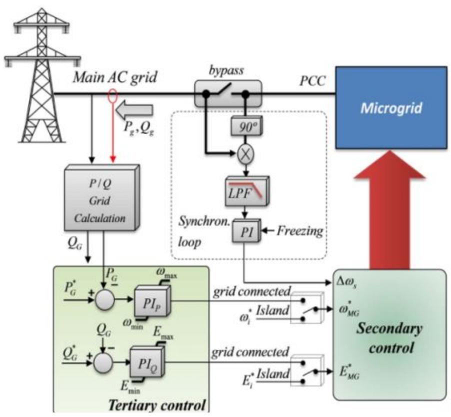

Fig. 4.(b). Tertiary control and synchronization loop of an ac MG.

d) Tertiary Control

When the MG is operating in grid connected mode, the power flow can be controlled by adjusting the amplitude and frequency of the voltage inside the MG [36]–[38]. The tertiary control block diagram shown in Fig. 4(b), PG and QG can be compared with the desired P∗G and Q∗G.

$$\omega_{MG}^* = k_{pP}(P_G^* - P_G) + k_{iP}\int(P_G^* - P_G)dt \quad (14)$$

$$E_{MG}^* = k_{pQ}(Q_G^* - Q_G) + k_{iQ}\int(Q_G^* - Q_G)dt \quad 15)$$

B. Hierarchical Control of DC Mgs

The drawbacks of ac MGs are the inrush currents due to transformers, reactive-power flow, harmonic currents, need for synchronization of the distributed generators, and three-phase unbalances. in addition, there is an growing interest to integrate prime movers with dc output, such as dc energy storage systems like batteries, super capacitor modules PV modules, fuel cells, and [39]–[43]. for instance, a dc distribution system or dc/ac converter connected to the grid or an ac MG part.

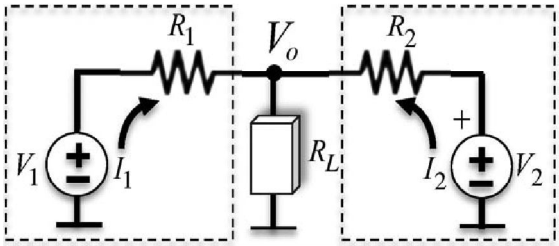

Fig. 5.Equivalent circuit of two parallel-connected dc power supplies.

a) Primary Control

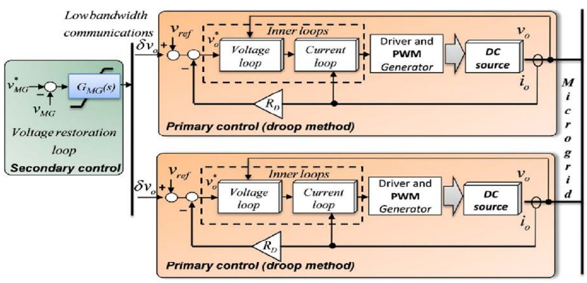

Fig. 6.Primary and secondary controls of a dc MG.

The output voltage in virtual impedance loop can be expressed as [44]:

$$v_0^* = v_{ref} - R_D \cdot i_0 \quad (16)$$

Where i_0 = output current, R_D = virtual output impedance, and v_{ref} = output voltage reference at no load. Assuming that $\in_v$ is the maximum allowed voltage deviation, R_D and v_{ref} must be designed as follows:

$$v_{ref} = v_n - \in_v / 2 \qquad (17)$$

$$R_D = \in_v / i_{\max} \qquad (18)$$

The output impedance of the resistive circuit is given to the power converters to compensate the difference between the voltage references $\Delta v_0^* = v_{01}^* - v_{02}^*$. Thus, the current sharing between the two converters $\Delta i_0 = i_{01} - i_{02}$ can be expressed as follows:

$$\Delta i_0 = \Delta v_0^* / R_D \qquad (19)$$

b) *Secondary Control*

A secondary control is proposed to solve the problem of the voltage deviation. v_{MG} Voltage level in the MG is sensed and compared with the voltage reference v_{MG}^*, and the error processed through a compensator is sent to all the units δv_0 to restore the output voltage (see Fig. 6). The controller can be expressed as follows:

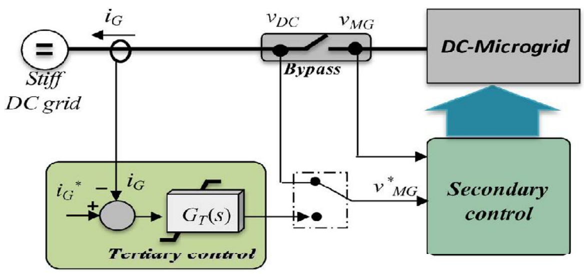

Fig. 7. Tertiary control and synchronization loop of a dc MG.

$$\delta v_0 = k_p (v_{MG}^* - v_{MG}) + k_i \int (v_{MG}^* - v_{MG}) dt \qquad (20)$$

Notice that δv_0 must be limited in order not to exceed the maximum voltage deviation. Finally, (16) becomes

$$v_0^* = v_{ref} + \delta v_0 - R_D \cdot i_0 \qquad (21)$$

c) *Tertiary Control*

Once the MG is connected to the dc source, the power flow can be controlled by changing the voltage inside the MG. As can be seen in Fig. 7, the current i_G, which is measured through the static by pass switch can be compared with the desired positive or negative current i_G^* (or power), depending on import or export energy.

The controller can be expressed as follows:

$$\delta v_0 = k'_p (i_G^* - i_G) + k'_i \int (i_G^* - i_G) dt \qquad (22)$$

V. EXPERIMENTAL RESULTS

The proposed application has been approved by simulation results as shown below.

A. Input power:

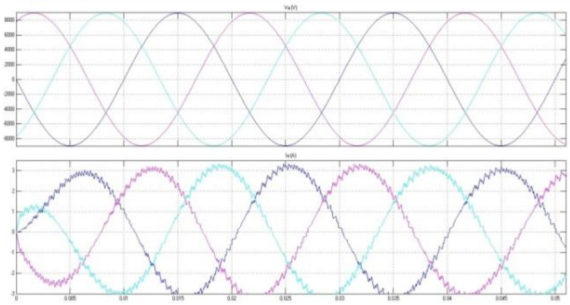

Fig. 8. Input side voltage and current waveforms

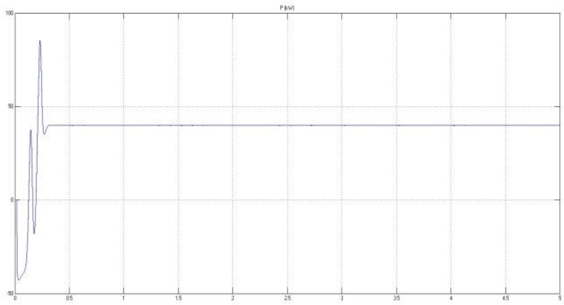

Fig.9. Input side power waveform

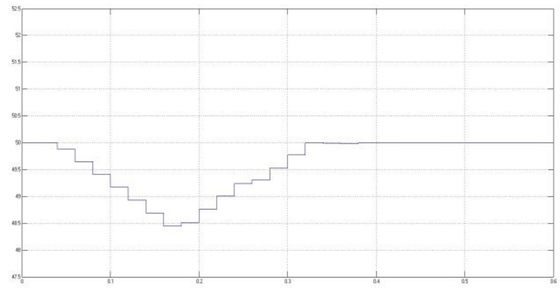

Fig.10. Frequency waveform

B. Grid power:

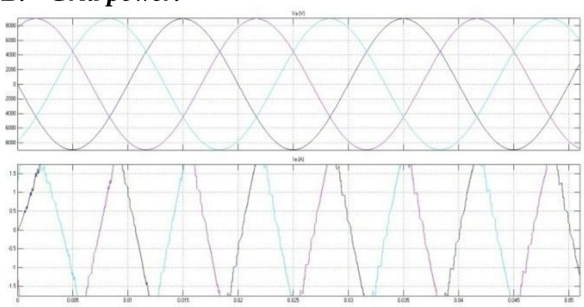

Fig.11. Grid side voltage and current waveforms

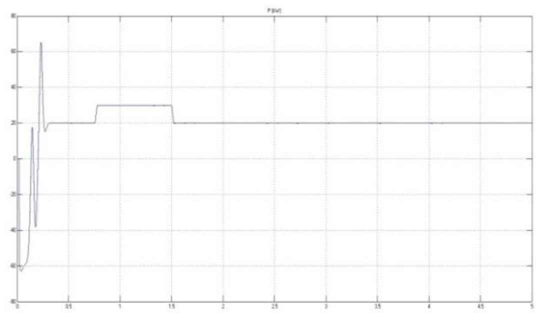

Fig.12. Grid side power waveforms

C. Load power:

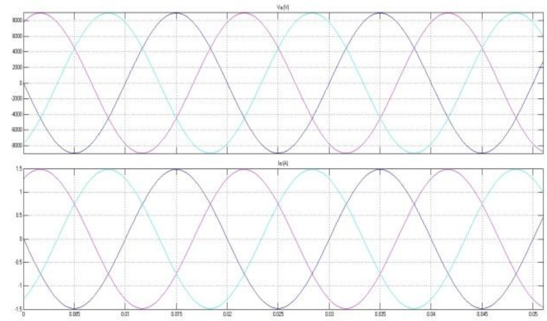

Fig. 13. Load side power supplied voltage and current waveforms

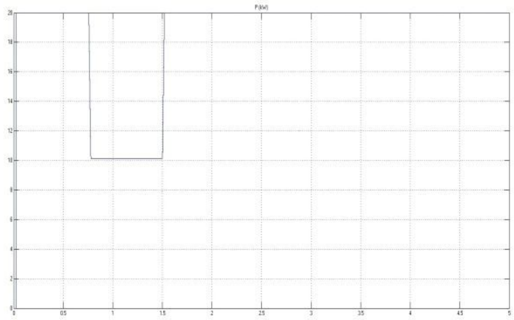

Fig.14. Load side power supplied waveforms

D. Comparison of input, grid and load side powers in a single plot

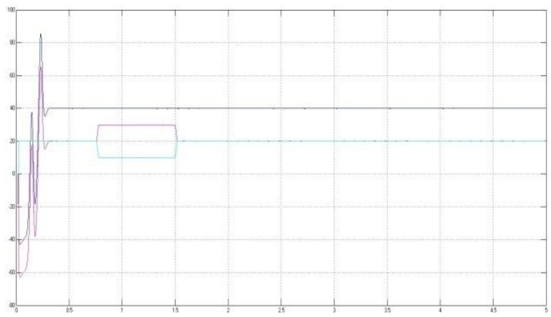

Fig.15. comparison of input, grid and load side power waveforms

CONCLUSION AND FUTURE TRENDS

This paper presented a universal approach of hierarchical control for MGs. The hierarchical control stems from standard ISA-95. AC and DC MGs controlled by 3 level converters. On the other hand, the hierarchical control of DC MGs with novel features can be useful in distributed power systems applications, such as telecommunication dc-voltage networks etc.

Consequently, flexible MGs are obtained can be used to control the power flow from the MG to these systems. In addition, these MGs are able to operate in both island and stiff-source-connected modes.

A superior control level could send all the references to each cluster of MGs to restore the frequency and amplitude. Finally, the tertiary cluster control can fix the active and reactive power to be provided by this cluster. As a result, we could scale the hierarchy of control as necessary.

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