General Control Methodology for Interconnected Mini-Grids

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Abstract: - Electricity is the main pillar of human activities, social development and economy growth. Due to the increase of world population and technologies, electricity demand has been rapidly and continuously increasing globally. In order to handle the increased demand, more power plants are built to satisfy consumer demand. However, the use of micro-generation with renewable energy sources is an alternative environment friendly option to provide energy. This alternative option can improve its quality and reliability, when mini-grids are linked to operate in parallel. This paper presents a management strategy for the power distribution in interconnected mini-grids. Using the proposed strategy, power distribution will be modular, flexible and scalable which leads to expand the rule of mini-grids.

Key-Words: - Distributed Generation, Micro-generation, Mini-Grid, Interconnected Mini-Grids, Droop Control Function, Energy Conversion System.

1 Introduction

The electric energy demand of the world is continuously increasing, and the vast majority of it in most countries is generated by conventional sources of energy. However, the rapid growth of global climate change along with the fear of an energy supply shortage and limited fossil fuel is making the global energy situation tends to become more complex. The increasing demand for electric power than the offer, along with many developing countries lacking the resources to build power plants and distribution networks, and the industrialized countries that face insufficient power generation and greenhouse gas emission problem forces us to consider a better economical and environmental friendly alternative. Implementing renewable energy sources (RESs) such as wind turbines, solar panels and fuel cells into interconnected mini-grids could be part of the solution [1-5].

However, all of these sources require interfacing units to provide the necessary interface to the grid. The core of these interfacing units is power electronics technologies because they are fundamentally multifunctional and can provide not only their principle interfacing function but various utility functions as well.

The key responsibility of the interconnection system is to control and maintain frequency and voltage of the power system. This is currently done using synchronous generators in many interconnected power systems. It is also possible to do this role with other generation technologies through their interface unit to the grid, namely the inverter. A control strategy which elegantly categorizes these units into grid-forming, grid-supporting and grid-parallel according to their functionality was introduced in [5] and will be used here.

This paper presents an efficient strategy to control the interconnection of mini-grids pool. Fig.1 shows the overview of the proposed strategy. The main aspect is to link mini-grids to interact and operate in parallel to form large smart grid. In each mini-grid, there are units' controllers and local supervisory control unit to regulate and maintain the voltage and frequency. The local controller manages power sharing between the source units along with user settings, rated power and metrological forecasting. Each link contains measurement units to observe information of power flow, while communicating with the main supervisory control. The main supervisory control integrates all information from local supervisory control units to optimize and control power dispatch and load sharing for the whole power system.

An obvious advantage is that when mini-grids operate in parallel then they can back each other up in case of failure and allow economical dispatching. The parallel

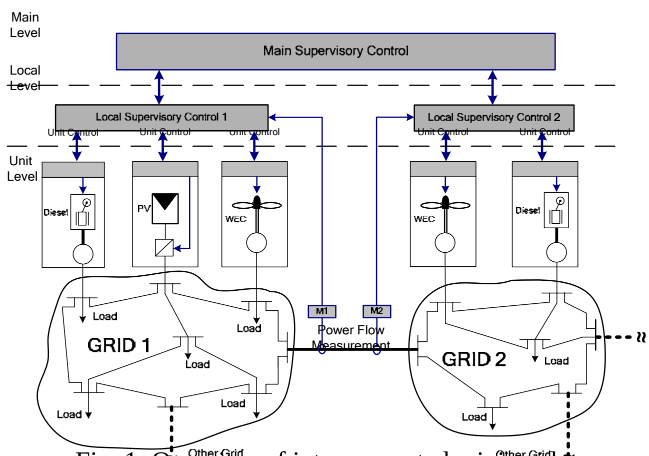

Fig. 1: Overview of interconnected mini-grids.

connections of the subsystems also improve security and protection. This proposed strategy will bring flexibility and modularity to the power system and will allow extension of loads and generation in electric power system.
This paper is structured as following: First, the mini-grid main components are explained. Second, the control methodology of the mini-grid will introduced including the rule of inverters. Third, the proposed control and management concept for the interconnection between the mini-grids will be introduced, including the control methodology between generator and inverters.

2 Mini-Grids Components

This section introduces mini-grid concept including the main components as shown in Fig.2. There are many components and control strategies which have to be taken into consideration for establishing the mini-grid. In general, mini-grids consist of four main components. These are generation, energy storage systems, communication and interfacing units. Generation sources are one of the important components of the mini-grid. However, there is a limited potential of generation sources when it operates in an isolated grid due to their intermittent nature. Thus, it is important to pay attention on the selection of suitable system architecture and the proper way to implement it. Energy storage systems can be used to assist the power distribution to deliver power without intermittent of electricity. Communication is another essential component to increase efficiency of power distribution. Finally, power electronic devices are the system core. These components are described as following:

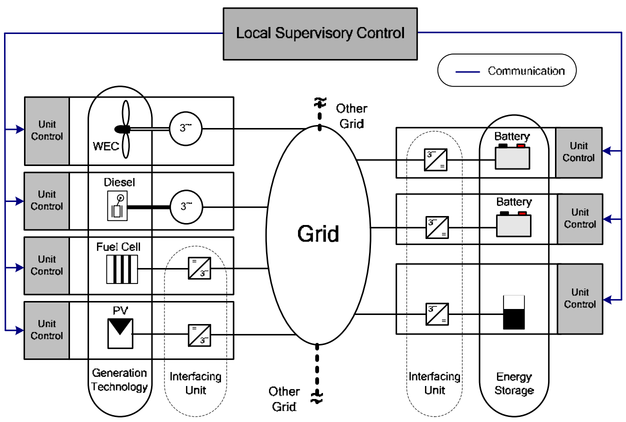

Fig. 2: Mini-grid concept.

2.1 Generation Technology

Power plants (Generators) typically utilize energy sources such as fossil fuel (gas, oil, and coal), nuclear fuel (uranium), geothermal energy (hot water, steam), and hydro energy (water falling through a head) into electricity. However, the trend is shifting to use micro-generation technologies. These micro-generation technologies are the main component of the distributed energy system. The approached strategy should be competent with these recent technologies.

2.2 Energy Storage Systems

The intermittent nature of the electricity from renewable energy systems is apparent since it is usually weather dependent. Therefore, to improve the supply reliability and to avoid intermittently, the distributed power system should be assisted by energy storage systems. In [6], many energy storage systems are explored including different technologies, capabilities and applications. It is expected that energy storage systems will be more established at the medium and low voltage grid levels. Detailed comparison of different technologies for example, mechanical energy storage (flywheels, compressed air and pumped hydro storage), electric field energy storage (ultra capacitors) and chemical energy storage (batteries, biogas and hydrogen fuel cells) are in [7-8]. These energy storage systems are essential to bring stability into the power system.

2.3 Communication Technologies

The information and communication technologies (ICT) are essential to improve the power system. the application of ICT to automate various functions such as meter reading, billing, transmission and distribution operations, outage restoration, pricing, and status reporting. The ability to monitor real-time operations and implement automated control algorithms in response to changing system conditions is just beginning to be used in electricity. Distributed intelligence, including "smart" appliances, could drive the co-development of the future architecture.

2.4 Interfacing Units (Power Electronics)

Power electronics such as inverters are important components to couple different energy conversion systems and to manage their operation regarding grid state variables (frequency and voltage). In [9], the interface units are modular and flexible which means it can be easily integrated, rescaled and expanded by adding new functional methods. As results, the distributed sources can be actively integrated into the grid control strategy and contribute to supply stability. This makes the distribution system more reliable and flexible. Moreover, it will lead to cost reduction in, production, installation and operation.

3 Control Methodology for Mini-grids

A mini-grid is build up normally by combination of renewable energy sources, conventional energy systems, and storage systems. The two common connection modes of the energy sources to the grid are common AC or DC buses [10].

The power produced by the energy conversion source (ECS) is fed through the DC-DC converter, and then this DC power is fed to the grid through the inverter. The inverter produces an AC output of a specified frequency and voltage. In the philosophy of feeding mode as shown in Fig.3, the power flow from an ECS into the grid may be driven by the grid or by the ECS itself [5, 9, 11-12]. In a grid driven feeding mode, the power flow from the ECS is controlled regarding the power requirements of the grid while in an ECS driven feeding mode, the power flow is controlled according to the requirement of the ECS itself.

A grid feeding mode can be realized through two different cases which are grid-forming and grid-supporting. An ECS feeding mode may be realized through a grid-parallel. A grid-forming case is responsible for establishing and maintaining voltage and frequency of the grid. This is done by adjusting its power production to keep the power balance in the system. A grid-supporting case produces predefined amount of power which is normally specified by a management control unit. These predefined amounts of power can be adjusted according to the system requirements and user settings via the management control unit. A grid-parallel case is a power production unit. Renewable energy sources in this mode such as wind energy and photovoltaic systems will give their maximum power as it can to feed into the grid (standard applications in conventional grid).

In addition, with the management and control topologies in [5, 12], a mini-grid can be designed via paralleling inverter units with different operating functions (grid-forming, grid-supporting and grid-parallel) and power rating as shown in Fig.4. This ensures that the system has expandability and flexibility.

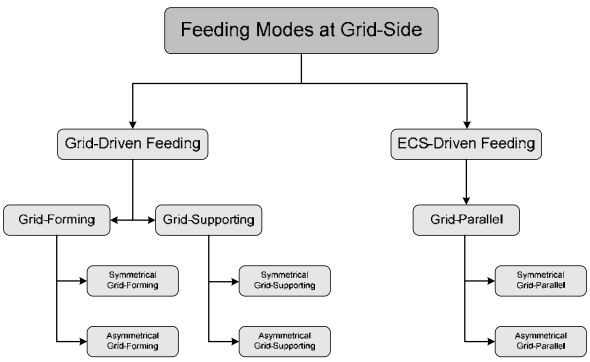

Fig.3: Feeding modes related to the grid side [5].

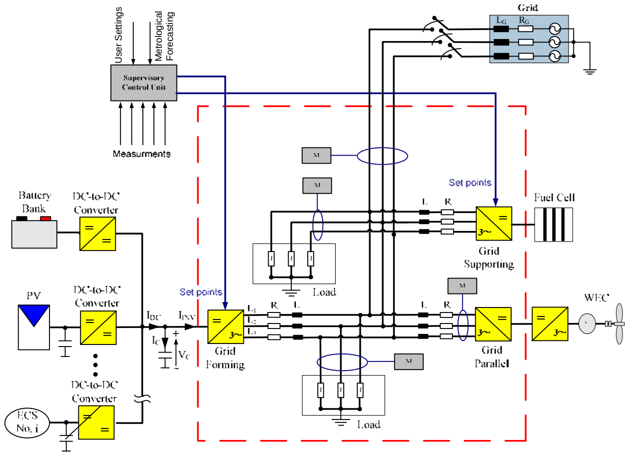

Fig.4: Desired system structure with different inverters.

4 Control and Management Concepts for interconnecting Mini-grids

Nowadays, a great deal of electrical energy is generated by large-scale generation using fossil fuels (e.g. oil, gas and coal), nuclear and hydro-power plants. In addition, main delivery process is through conventional distribution (centralized) where the power flow is in one direction. This starts from the electricity generation, and goes through electric power transmission, electricity distribution and electricity retailing respectively. To handle the growth of electricity demand, many interconnected systems of large power plants have been established and operated around the world, for example, the interconnected grid in Europe and The Seven Countries Interconnection Project (SCIP). However, the interconnected systems of power plants are not suitable for rural regions of developing countries since the rural settlement is scattered and the cost of grid extension is very high.

One solution is to implement decentralized generation where mini-grids are integrated to operate in parallel. The power flow of such system will be bi-directional which allows power flow exchanges between the mini-grids. The link connections between the grids are the main objective of this section. This will lead to the control of the state variables in mini-grid (voltage and frequency) and will increase the reliability and protection of power distribution.

This section is separated into two sub-sections. First, the communication structure of unit controllers, local supervisory controllers and main supervisory controller is described. Second, power balancing control strategy between the interconnected mini-grids is explained. An example of the link is given and control strategy for the interconnection link combined with the control methodology of inverters will be also introduced.

4.1 Control Strategy of Interconnected Grids

The main operation control of the link connections is managed by the main supervisory controller which communicates with the local supervisory controllers to optimize the system performance. It is important to implement a control strategy by using clustering of local supervisory controllers and grid together. This will lead to single interface to the power system which maintains the cost reduction. The proposed strategy provides smooth transition in parallel operation with reliability. Moreover, it increases the robustness of the power system with fast control operation because each individual system has its own characteristic and operation to control frequency and voltage.

There are many possibilities of the control strategy to manage the link connections of interconnected mini-grids. One approach is using intelligent switch to manage the link between the grids as explained in [13]. The switch will automatically detect disturbances such as faults in its local mini-grid. The intelligent switch strategy is to observe the frequency and phase angles at the connection point. Whenever the fault occurs, the switch will be opened. Then that mini-grid will no longer connect to other grids. It will island and maintain the system voltage and frequency itself. However, to maintain the system, it will depend on each mini-grid control strategy. After clearing faults, the intelligent switch of that mini-grid will be closed which means the mini-grid will unite with other mini-grids again. In addition, during the fault and stabilization period, other mini-grids are still parallel operated together by the link connections.

Another option is to control the power flow of the link connections between the grids. These links can be possibly managed via the power flow of all mini-grids as shown in Fig.5.

A local supervisory controller considers local automatic controllers and protection (i.e. frequency control, voltage control and power quality). It will detect the power flow on every grid connected link. Whenever faults occur or switches open, the local supervisory controllers will automatically manage to maintain frequency and voltage of mini-grid within the accepted ranges. This is done with respect to their power rating, set values and metrological forecasting. Moreover, the local supervisory controllers will communicate with the main supervisory control responsible for the energy management (i.e. supervisory control optimization, dispatch control strategy, control and communication management).

The main supervisory controller is used to decide which control strategy of each mini-grid should be selected to react to the failures or load variation. Afterwards, the main supervisory controller will communicate back to all local supervisory controllers and each of these will signal the units controllers to control and maintain

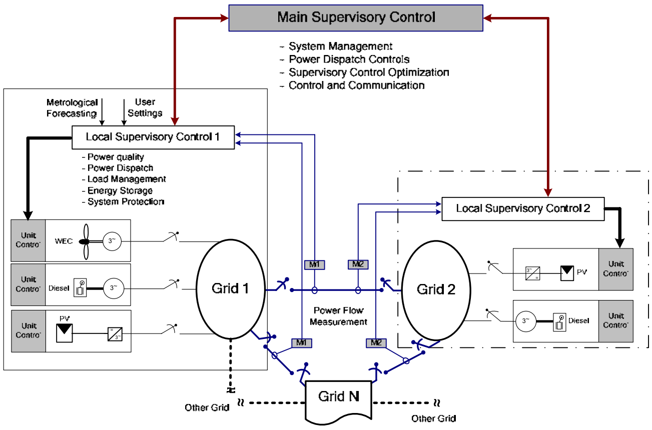

Fig. 5: Control strategy of the interconnected mini-grids.

frequency and voltage in the mini-grid. The communication structure of the main supervisory controller, local supervisory controllers and unit controllers is shown in Fig.6.

There are various different control strategies that are available for implementation in mini-grids. This depends on factors such as generation types, interface units and desirable communication. These requirements dissimilarities will lead to different system characteristic. Therefore, a new power balancing control strategy for interconnected mini-grids will be introduced.

4.2 Power Balancing Control Strategy of Interconnected Grids

This section introduces control strategy for interconnecting mini-grids using power balancing control (e.g. droop control function) which is implemented and used in conventional systems. Each link between mini-grids will be individually controlled and managed by local supervisory controller. In this proposed example, the total power in the links and frequency of the grid will be used.

Fig.7 shows an example of the power balancing control

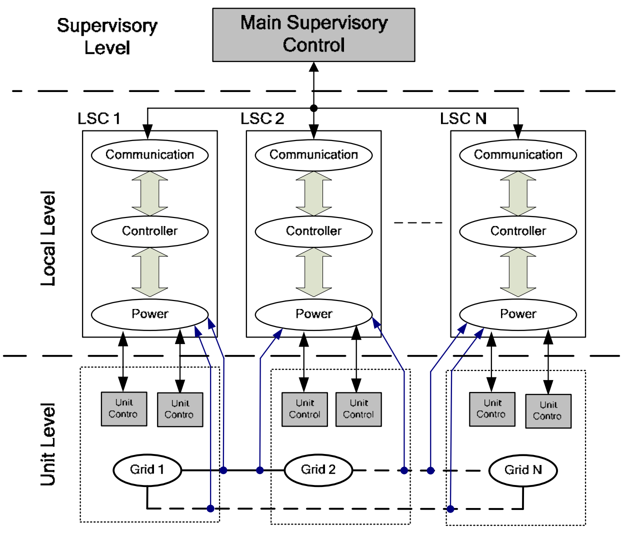

Fig. 6: Communication structure of control units.

strategy for the interconnection of mini-grids amid by two mini-grids connected together. One mini-grid contains two synchronous machines as an example of generating sources. For the proposed control strategy, there are two droop control functions which are implemented in the power system. One is the droop control function for the power sharing among the link connection of the grids. The other droop control function is implemented in each generating unit of each mini-grid. The total droop factor of the whole power system equals to the summation of the droop factors in every mini-grid. The droop factors of mini-grids also contain the droop factors of each generating unit.

At steady state, if disturbances, failures or load changes happen in mini-grid, other mini-grids will help by producing more power to help the faulty mini-grid. For example, in Fig.7, total power of grid 1 to grid 2 (P_{12}) is the same as total power of grid 2 to grid 1 (P_{21}). Each time when a fault occurs (e.g. generating units of mini-grid 2 are corrupted), the additional power will flow from grid 1 to grid 2 to stabilize the system. It means that P_{12} is higher than the reference power and P_{21} is less than the reference power. At the same time, the frequencies of each mini-grid will also change due to the failure. To control the power balance of the interconnection mini-grid, the power sharing between the links can be solved by droop control system. A full droop control system consists of frequency droop

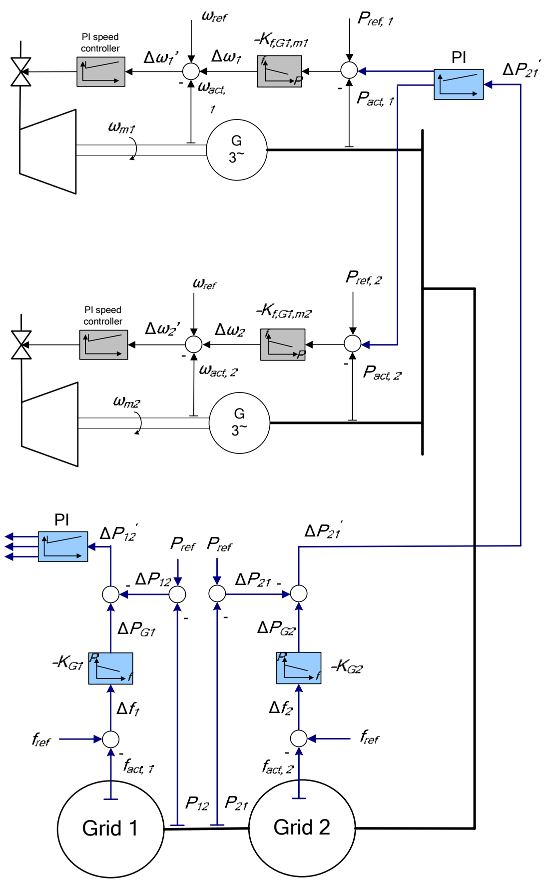

Fig. 7: Example of control strategy in interconnected grids.

controller and voltage droop controller. The frequency droop controller of the grid is determined by the relationship between a reference frequency and the frequency of the grid. The frequency droop operates as offset with respect to a constant nominal frequency. It means the reference frequency can be varied in acceptable percentage range. Therefore, with the summation of droop and offset power of the links, the controller will pick up load, if the power system frequency falls and will drop load if the power system frequency rises. As result, the power flow in the line will be totally controlled.

Droop control functions must be implemented into generation units to prevent any generation unit from taking the entire load. When the failure or load variation occurs at other grid or the individual grid, it will have an effect also on the terminal voltages of the synchronous machines. This will also relate to current flow in the stator part of the synchronous machine. This current is proportional to the electromagnetic torque (T_e). Therefore, the machine will signal the valve which used for stabilizing the mechanical torque (T_m) to maintain the angular speed of the generator (ω_m) during any disturbance. Similarly to frequency droop controller of each generating unit, the voltage droop controller's objective is to maintain the terminal voltage close to nominal value. As results, with this automatic control strategy for the generation, the connections between grids will be simply managed and controlled to maintain the terminal voltages constant at any load variation and faults. The main advantage of using two droop loops is that the load change of the entire interconnected mini-grid is shared among all units leading to overall system stability.

Future power distribution requires extra expandability and flexibility in the integration of distributed generation (DG). This is why the control strategy for the interconnected grid should be combined with control methodology of inverters (grid-forming, grid-supporting and grid-parallel).

To implement a control methodology of inverters into interconnection system, it requires a synchronization, load management and load sharing with respect to the rating and metrological forecasting. A general layout of control structure of interconnected mini-grids including combination of a synchronous machine and grid-forming case is shows in Fig.8.

In the grid-forming case, the state variables (voltage and frequency) are directly controlled and formed by inverters. The power injection in the connection point of the inverter is related to active and reactive power controllers. More details of grid-forming are discussed in [5, 9]. The synchronization and load sharing are also required in a grid-forming case. However, the control strategy of grid-forming can be modified using the droop control function. The droop factors are also related to the

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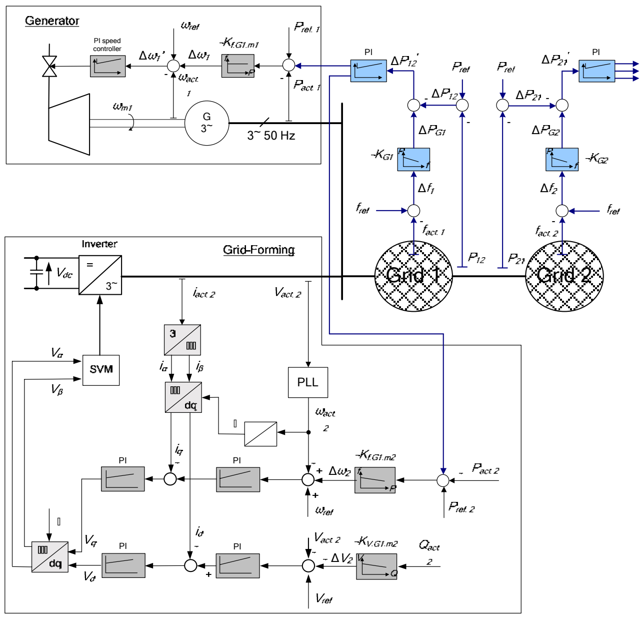

Fig. 8: Example of the mini-grid control strategy.

total droop factor of the power system. In the control scheme of grid-forming mode, the voltage is controlled by the d-component. The voltage droop is related to the reactive power variation of the grid. In contrast, the frequency is controlled by the q-component which is related to active power. At this point, the power controlled from the link will be also managed into the control strategy of the grid-forming case. Moreover, due to the flexibility and expandability of inverters' control strategy, different feeding modes of inverters can be implemented.

5 Conclusion

Power distribution is one of the key factors to make the power system more efficient. One solution is to bring the energy supplies close to the customers or so called distributed generation. This also includes the use of environment friendly renewable energy sources. However, due to the rapid growth of electricity demand globally, efficient management strategies of power distribution are definitely needed to handle the large requirements in the future.

This paper introduces a novel control methodology for interconnected mini-grids. The proposed strategy is bringing the mini-grids to operate in parallel using link between the mini-grids. The load sharing and power dispatch of the links can be automatically managed via the unit controllers, local supervisory controllers of each mini-grid and the main supervisory controller according to their ratings, metrological parameters and user settings.

This control strategy improves the power distribution system due to its fast response, reliability, flexibility and efficiency. With the proposed strategy, mini-grids can be expanded to form a huge smart power system.

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