Control and Optimization of Smart AC/DC Hybrid Microgrids

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Abstract - *As a new developed concept, microgrids evolved to AC/DC hybrid microgrids where each system, AC and DC, has its own generations, storages and loads. The AC and DC systems are linked with interlink convertor (IC) which transfers the power between the AC and the DC system depending on the specific requirement. In this paper, the control strategy of AC/DC Hybrid Microgrid is modelled using state space representation and regulated using the droop control. The output response which is IC current is simulated using MATLAB as open loop system, with Proportional Integral (PI) controller and with Linear Quadratic Regulator (LQR) controller. The simulation is performed for two cases of power transfer from AC to DC network and from DC to AC network. The LQR controller allows the power transfer in fast, robust and stable manner against various operational modes. In addition, the LQR controller can be implemented for the multiple input/multiple output system more efficiently than the PI controller.*

Key Words: AC/DC Hybrid Microgrids, PI Controller, LQR controller, IC Convertor.

1. INTRODUCTION

Microgrids can be connected to the utility grid in the normal operation mode, or they can operate in a stand-alone mode in case where the main connection to the grid is not available. Microgrids consist of distributed generation, energy storage and variable loads. The development of the renewable energy and the need to integrate them into the grid is one of the motives to develop Hybrid AC/DC micro grid. Most of the utility supply is AC, however the renewable energy and the new load are mostly DC. In AC/DC hybrid microgrids, each system, AC and DC, has its own generations, storages and loads. The AC and DC systems are linked with interlink convertor (IC) which transfers the power between the AC and the DC system depending on the requirement.

In the grid connected mode, the convertor controls the transfer of the active and reactive power to the main grid. In the stand-alone mode, the main function of the convertor is to insure a smooth transition of the power from the AC to the DC system and via versa. The power transfer is determined by the frequency and voltage droop control which depends on the available power/demand on each side of the convertor. For this power transfer, a Linear Quadratic Regulator (LQR) controller is proposed for the interlink convertor to insure stability, fast response and minimum or zero overshoot. The performance of the LQR is compared to the open loop system and with the PI controller controlled system [1].

In [2] the Hybrid AC/DC micro grid is proposed to reduce the energy losses due to the energy conversion. Moreover, an overview is provided about the hybrid AC/DC grid and its major challenges such as detection of island mode, system stability and the control and protection scheme. In [3] the Power Management System (PMS) for the AC/DC microgrids, control shame and operating mode are discussed. In addition, the different structure (AC/DC couple and DC-AC couple), different control strategies and power management scheme for different type of micro are presented. In [4] the load maximization is achieved in the hybrid AC/DC microgrids by the optimal power flow formulation. This maximization is very essential especially in the island mode where many convertors and plug-and-play capabilities bring some challenges to the microgrid. The objective of this optimal power flow controller is to increase system stability. The problem is formulated by non-linear optimization problem and solved using the Interior point method and tested on a 38-bus AC/DC microgrid. Economic model predictive control (EMPC) is proposed in [5] as cost-effective control of the hybrid microgrids. The objective of this model is to operate at the pricing level decided for the microgrid. For the hybrid microgrids, a control system with three level hierarchy is proposed in [6]. The control system is designed for the AC/DC and DC/AC convertors for both standalone and grid connected operation modes. In the first control level, a local droop control is proposed using a proportional controller. The second control level is to control the voltage variation on the DC bus which is caused by the local droop control. The third level of control is to manage the interface with the external grid. In [7], the author proposes a three level control system which is similar to the control system developed in [18]. However, it is based on ISA-95 and electrical dispatching standards. This proposal is designed in line with the efforts towards Microgrids standardization. In [8], a local power sharing is proposed which doesn't require any communication to minimize the power conversion and reduce the cost.

1.1. AC/DC Hybrid Microgrid Configuration

The proposed AC/DC Hybrid Microgrid consists of the two sub-grids (AC and DC grid) as shown in Figure 1, with the following components and voltage levels:

AC network	**:230Vac**
• Utility connection	:25kV
• Wind turbine	:20-kW
• Diesel generator	:100-kVA
• Capacitor bank	:10kVAR

DC network **:600Vdc**

- Photovoltaic array :25kV
- Battery Energy Storage Systems (BESS) :30 kW

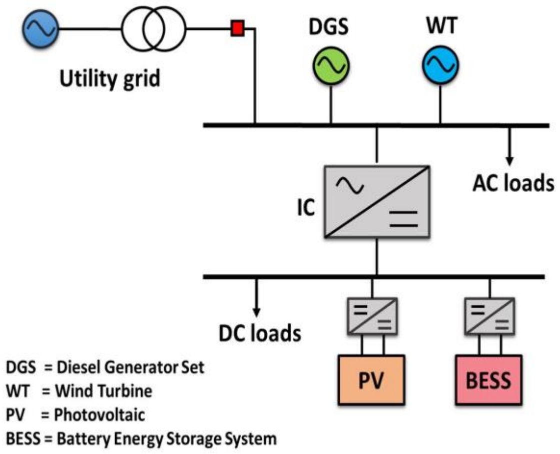

Figure 1: AC/DC Hybrid Microgrid Configuration [1]

1.2. AC/DC Hybrid Microgrid Operation

The interconnection between the AC and DC system is implemented via a bi-directional convertor with R-L filter. The system is stable while the microgrid is connect to the utility grid connection as it can supply the demand of the AC and DC loads. Once the microgrids is disconnected then all the distributed generators with the BESS will supply the power to the load and the convertor will transfer the power from AC/DC according to the droop control explained below. The power transfer through the convertor can introduce some instability to the microgrid.

2. DROOP CONTROL STRATEGY

The configuration of the proposed bidirectional AC/DC convertor is shown in Figure 2. From the DC grid side, a capacitor is added at the common DC point while a RL filter is used to connect the convertor to the AC grid. In case the droop control of each sub grid is not sufficient to overcome the power imbalance then the power shall be shared between the AC and DC grid. While transferring the power from one grid to the other, the convertor will be considered as a source for the grid with the power imbalance while it is considered to as a load for the other grid. As the active power variation in the AC grid is measured by the frequency variation and the active power variation in the DC grid is measured by the voltage as explained earlier, the measurement of both grid shall be normalized so that they can be compared as per equations (1) and (2).

$$\Delta f = \frac{f_{ref} - f_{ac}}{0.5(f_{max} - f_{\min})} \text{x} \frac{1}{R1} \quad (1)$$

$$\Delta V_{dc} = \frac{V_{dcref} - V_{dc}}{0.5(V_{dcmax} - V_{\mathrm{dcmin}})} \text{x} \frac{1}{R2} \quad (2)$$

where f_{ref}, V_{dcref}, R_1 and R_2 are the reference frequency of the AC grid, the reference voltage of the DC grid, the gain of frequency variation and the gain of the DC voltage variation respectively. The comparison between the normalized measurement will decide the direction of the power transfer as per equation (3) based on the Active Power reference (P_{IC}).

$$P_{IC} = \Delta f - \Delta V_{dc} \quad (3)$$

The convertor will transfer the power from AC to DC if P_{IC} has a negative value. On the other hand the power will be transferred from DC to AC if P_{IC} has a positive value. In the proposed hybrid microgrid, the convertor can transfer 20 kW on both direction and it has the following droop control characteristics as shown in Figure 2:

- Frequency range is (58 Hz-62 Hz)
- DC voltage range is (550 V-650 V)

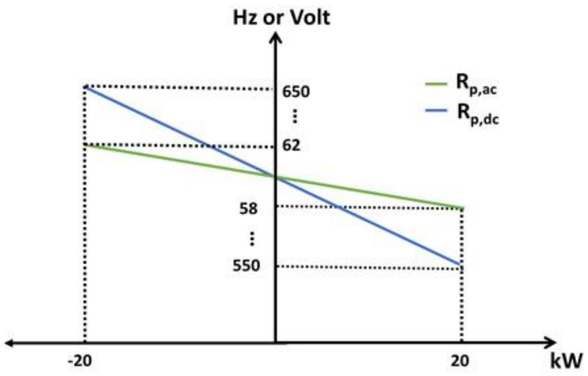

Figure 2: AC/DC convertor droop control [1]

3. Optimal LRQ CONTROLLER DESIGN

An optimal controller is deigned to insure stability, fast response and minimum overshooting with minimum cost to the system. The optimal LQR controller will be designed by selecting the most suitable Q and R matrices to obtain the least performance cost and meet the required output. Moreover, the response of the system with LQR controller will be compared to open loop system and to the Proportional Integral (PI) controlled system.

3.1. Design Procedure

To design the system as per the requirement described above, the following procedure is followed:

1. Develop the system detailed block diagram.
2. Obtain the system differential equations.
3. Derive the system state variable model, in term of matrix A, B & C.
4. Derive the Cost Index formula considering the system specifications.
5. Optimize the cost function by the LQR method according to the system requirement.

6. Implement the optimal controller with the closed loop feedback.

3.2. Scheme Representation

As described before, the convertor has a capacitor (C) in the common DC link and it is connected to the AC grid via an R-L filter as shown in the Figure 3.

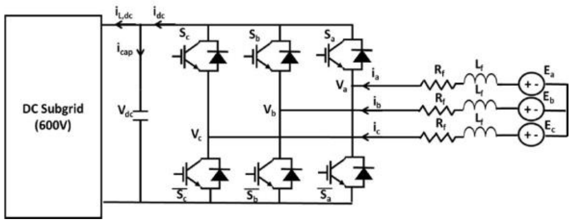

Figure 3: AC/DC Convertor Scheme [1]

The measured voltage and current at the convertor side are transformed to d-q axis using the PLL controller. Moreover, the reference currents I_{dref} and I_{qref} are obtained by PIC droop control scheme (3), then passed through a PI controller.

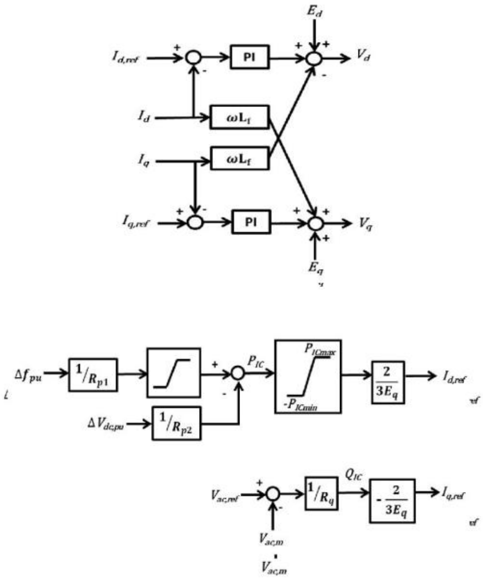

Figure 4: AC/DC convertor block diagram [1]

3.3. System Differential Equation

The system thee phase voltage can be obtained as per equation (4);

$$V_{abc}(t) = -R_f i_{abc}(t) - L_f \frac{di_{abc}(t)}{dt} + E_{abc}(t) \quad (4)$$

where R_f and L_f are the filter resistance and inductance, respectively. The system current and voltages are

$$i_{abc\,(t)} = \begin{bmatrix} i_{a(t)} \\ i_{b(t)} \\ i_{c(t)} \end{bmatrix}, \qquad V_{abc\,(t)} = \begin{bmatrix} V_{a(t)} \\ V_{b(t)} \\ V_{c(t)} \end{bmatrix}, E_{abc\,(t)} = \begin{bmatrix} E_{a(t)} \\ E_{b(t)} \\ E_{c(t)} \end{bmatrix}$$

The current equation is given as follows,

$$\frac{di_{abc}(t)}{dt} = -\frac{R_f}{L_f} i_{abc}(t) - \frac{V_{abc}(t)}{L_f} + \frac{E_{abc}(t)}{L_f} \quad (5)$$

After the PLL transformation on the d and q axis, the rate of change of the currents are given as

$$\frac{di_d(t)}{dt} = -\frac{R_f}{L_f} i_d(t) + \omega i_q(t) - \frac{V_{dc}(t)}{2L_f} + \frac{E_d(t)}{L_f} \quad (6)$$

$$\frac{di_q(t)}{dt} = -\frac{R_f}{L_f} i_q(t) - \omega i_d(t) - \frac{V_{dc}(t)}{2L_f} + \frac{E_q(t)}{L_f} \quad (7)$$

3.4. State Model Representation

The final state space model can be presented as shown below

$$\begin{bmatrix} \dot{x_1}(t) \\ \dot{x_2}(t) \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega \\ -\omega & -\frac{R_f}{L_f} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{bmatrix} - \frac{V_{dc}}{2} \begin{bmatrix} \mu_1(t) \\ \mu_2(t) \end{bmatrix} + \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{bmatrix} \begin{bmatrix} E_d(t) \\ E_q(t) \end{bmatrix} \quad (8)$$

$$y(t) = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix}, \qquad \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} = \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix}, \quad \begin{bmatrix} \mu_1(t) \\ \mu_2(t) \end{bmatrix} = \begin{bmatrix} p_d(t) \\ p_q(t) \end{bmatrix}$$

As the AC coupling points are measurable, therefore they will be defined as follows

$$E_d = E_{ac} \;\; and \;\; E_q = 0$$

Therefore, the state space model can be reformulated in the following equations (9), (10) and (11)

$$\dot{x}(t) = A\,x(t) + B(Nu(t) + d) \quad (9)$$

$$u(t) = -\frac{d}{N} + u_m(t) \quad (10)$$

$$\dot{x}(t) = A\,x(t) + BNu_m(t) \quad (11)$$

where

$$A = \begin{bmatrix} -\frac{R_f}{L_f} & \omega \\ -\omega & -\frac{R_f}{L_f} \end{bmatrix}, \text{B} = \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & \frac{1}{L_f} \end{bmatrix}, N = -\frac{V_{dc}}{2}, \; d = \begin{bmatrix} E_{ac} \\ 0 \end{bmatrix}$$

In case the power transfer from AC to DC, the convertor acts as a rectifier and the state space model will become

$$\begin{bmatrix} \dot{x_1}(t) \\ \dot{x_2}(t) \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega \\ -\omega & -\frac{R_f}{L_f} \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \end{bmatrix} + \begin{bmatrix} \frac{N}{L_f} & 0 \\ 0 & \frac{N}{L_f} \end{bmatrix} \begin{bmatrix} \mu_{m1}(t) \\ \mu_{m2}(t) \end{bmatrix}$$

To remove steady state error and to include the droop control of the controller, an auxiliary set of state variables is introduced as follows,

$$X_I = \begin{bmatrix} X_{I1} \\ X_{I2} \end{bmatrix}, \; \dot{X}_I = r - y = r - CX \;, X_I(0) = 0$$

The reference ***r*** represent the reference current of the convertor droop control i_d^* and i_q^* . Therefore, the state space model will be augmented as follows,

$$\begin{bmatrix} \dot{x_1}(t) \\ \dot{x_2}(t) \\ \dot{x_{I1}}(t) \\ \dot{x_{I2}}(t) \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega & 0 & 0 \\ -\omega & -\frac{R_f}{L_f} & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_{I1}(t) \\ x_{I2}(t) \end{bmatrix} + \begin{bmatrix} \frac{N}{L_f} & 0 \\ 0 & \frac{N}{L_f} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mu_{m1}(t) \\ \mu_{m2}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ i_d^*(t) \\ i_q^*(t) \end{bmatrix}$$

In the other operating mode where the power transfer from DC to AC the convertor acts as an inverter, the state space model will be as given in equations (12) and (13),

$$\frac{di_d(t)}{dt} = -\frac{R_f}{L_f} i_d(t) + \omega i_q(t) + \frac{V_{dc}(t)}{2L_f} - \frac{E_d(t)}{L_f} \qquad (12)$$

$$\frac{di_q(t)}{dt} = -\frac{R_f}{L_f} i_q(t) - \omega i_d(t) + \frac{V_{dc}(t)}{2L_f} - \frac{E_q(t)}{L_f} \qquad (13)$$

Following the similar steps for the rectifier, the state space model of the invertor can be represented as follows in equation (14),

$$\begin{bmatrix} \dot{x_1}(t) \\ \dot{x_2}(t) \\ \dot{x_{I1}}(t) \\ \dot{x_{I2}}(t) \end{bmatrix} = \begin{bmatrix} -\frac{R_f}{L_f} & \omega & 0 & 0 \\ -\omega & -\frac{R_f}{L_f} & 0 & 0 \\ -1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_1(t) \\ x_2(t) \\ x_{I1}(t) \\ x_{I2}(t) \end{bmatrix} + \begin{bmatrix} -\frac{N}{L_f} & 0 \\ 0 & -\frac{N}{L_f} \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \mu_{m1}(t) \\ \mu_{m2}(t) \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ i_d^*(t) \\ i_q^*(t) \end{bmatrix} \qquad (14)$$

3.5. Cost Function

The quadratic cost function and the state feedback controller for the problem are given as follows

$$J = \int_0^{\infty} [x(t)^T Q x(t) + u_m(t)^T R u_m(t)] dt \qquad (15)$$

$$u_m(t) = -K_{LRQ}\, x(t) \qquad (16)$$

4. LQR CONTROLLER VALUES

Solving the above optimal control problem in (15, 16), MATLAB function, *lqr,* was used to calculate the feedback gains. Suitable values for the Q & R weighting matrixes were selected to suit the convertor model. First, an initial value of Q and R was selected based on the nature of the system. Then an iteration method was used to match the system requirement as following

$$Q = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, R = \begin{bmatrix} 0.001 & 0 \\ 0 & 0.001 \end{bmatrix}$$

The optimal state feedback controller was calculated as

$$K = \begin{bmatrix} -31.3075 & 0.000000 & 31.0171 & -6.1593 \\ 0.00000 & -31.3075 & 6.1593 & 31.0171 \end{bmatrix}$$

In addition, a PI controller is designed with

$$K_p = 0.5 \ \ and \ K_i = 0$$

The controllability matrix of the system was checked and the system was found to be controllable.

5. RECTVIER MODE POWER FLOW FROM AC TO DC

In this analysis, the microgrid is operating in the stand-alone mode. The DC load increased while the DC sources (battery and the PV array) are not sufficient. Therefore, the DC voltage encountered some variations, which will enable the droop control of the convertor to transfer power from the AC to the DC grid. The system transient performance is obtained in three different scenarios: convertor without any control (open loop system), convertor with PI controller and finally the convertor with the optimal LQR controller.

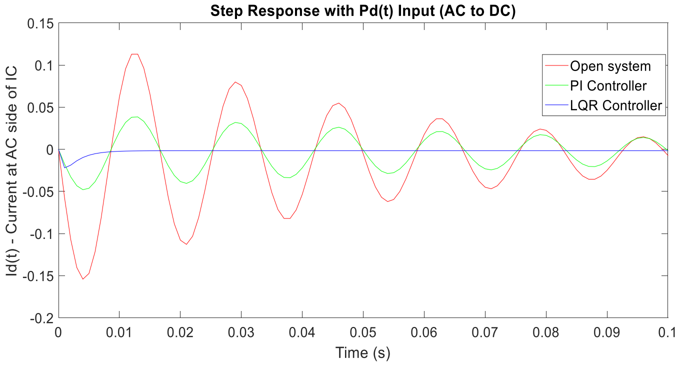

Figure 5: Step Response of Id(t) with pd(t) as input, AC to DC supply mode

The step response of the hybrid AC-DC Rectifier current has overshoot, steady state error and long settling time. This will affect the load connected to the microgrid which requires reliable and stable source of supply. In addition, as the microgrid is in the island mode, the supply from the utility is not available to overcome the impact of the transient effect once the AC grid supply power to the DC grid. By implementing the PI controller, it is noticed that the overshoot and steady state error were reduced, however the settling time was not improved.

The step response of the rectifier current with the LQR shows a lot of improvement as the overshoot, steady state error and settling time were improved. The system transient response became very smooth and robust with the power transferred from the AC to the DC grid. This is very essential for the microgrid operation especially in the island mode where the supply capacity is limited and the high quality of the power supply load is required. In general, the LQR controller allows the power transfer from AC to DC network in fast and stable manner; moreover, the microgrid response becomes more robust even in the island mode against various operation modes. Finally, the LQR controller can be implement for the multiple input and multiple output system more efficiently than the PI controller.

6. INVERTOR MODE POWER FLOW FROM DC TO AC

While the microgrid in the stand-alone mode, the increment of the AC load will decrease the frequency. The frequency reduction will trigger the droop controller of the convertor and the power will be transferred from the DC grid to the AC grid provided that the DC battery is fully charged. The system transient response is obtained in three different scenarios: convertor without any control (open loop system), convertor with PI controller and finally the convertor with the optimal LQR controller.

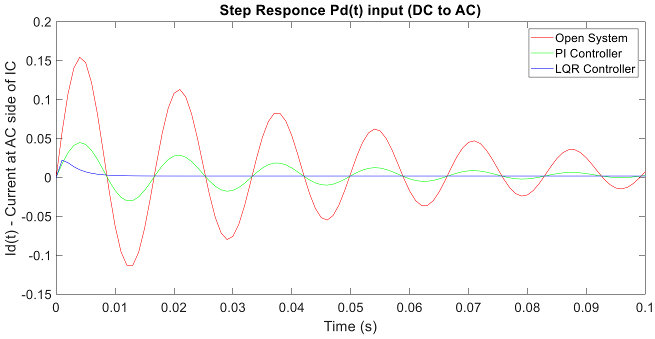

Figure 6: Step Response of Id(t) with Pd(t) as input, DC to AC supply mode

The step response of the hybrid DC-AC Invertor current has overshoot, steady state error and long settling time similar to the AC-DC transition. This will affect the load connected to microgrid which required reliable and stable source of supply as mentioned earlier. In addition, as the microgrid is in the island mode, the supply from the utility is not available to overcome the impact of the transient effect once the DC grid supply power to the AC grid. By implementing the PI controller, it is noticed that the overshoot and steady state error were reduced; however the settling time was not improved. The step response of the rectifier current with the LQR shows a lot of improvement as the overshoot, steady state error and settling time were reduced. The system transient response became very smooth and robust with the power transferred from the DC to the AC grid. This is very essential for the microgrid operation especially in the island mode where the supply capacity is limited, and the high quality of the power supply is required. In general, the LQR controller allows the power transfer from DC to AC network in fast and stable manner. Moreover, the microgrid response become more robust even in the island mode against various operation mode. Finally, LQR controller can be implemented for the multiple input and multiple output system case, which can be shown to be more efficient than the PI controller.

3. CONCLUSIONS

For power transfer in Microgrids from AC to DC and vice versa, a Linear Quadratic Regulator (LQR) controller is proposed (for the interlink convertor) to insure stability, obtain fast response and eliminate overshooting. The performance of the LQR is compared with the open loop system and the PI controller. The step response of the convertor current with the LQR shows a lot of improvement as the overshoot, steady state error and settling time were reduced. The system transient response became very smooth and robust with the power transferred from the AC to the DC grid and vice versa. This is very essential for the microgrid operation especially in the island mode where the supply capacity is limited, and the high quality of the power supply is required.

The recommendation for future work can be divided into two categories; work related to the system model and work related to the type of controller. The system model can be improved to include Power Management System (PMS), which shall provide a command to start the power transfer between AC to DC and vice-versa. The PMS insures the availability of the excess power from the source to avoid possible network distortion on both the AC and DC systems, while avoiding frequent switching between the two networks. For the type of controller, a faster and more efficient *digital* LQR controller may be used. The digital controller will have better interface with the smart network components. In addition, the digital controller is simpler in implementation and has more flexibility in the setting and adjustment. A second proposal is to use fuzzy controller which can be a more economical solution and covers wide range of applications.

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