Improved Control Schemes Used for Seamless Operation of Distributed Generation Inverter System in Grid-connected and Stand–alone Modes

A Research Plan

For

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Abstract:

The recent advances in renewable energy technologies and changes in the electric utility infrastructures have increased the interest of the power utilities in theutilization of distributed generation (DG) resources to generate electricity. Although their deployment is rapidly growing, there are still many challenges to efficient design, control and operate micro-grids when connected to the grid, and also when in islanded mode, where extensive research activities are underway to tackle these issues. Islanding describes the condition in which a microgrid or a portion of the power grid, which consists of a load and a distributed generation (DG) system, is isolated from the remainder of the utility system. In this situation, it is important for the microgrid to continue to provide adequate power to the load. In this study, a power control algorithm is introduced to control the active and reactive power in grid-connected mode and also the active power and voltage in the islanded mode operation. A robust controller is introduced to achieve the control objective in grid connected mode and island mode operation. The stability analysis of optimal controller for DG system is also proposed to analyze the stability with singular value based. The seamless transition between the grid connected and islanded mode has been proposed by using islanding detection, synchronization algorithm, and load shedding, current and voltage control methods. One of the most challenging problems in thedistribution network is island detection since it causes serious problems for equipment connected to the network, especially distributed generators (DG). An advanced island detection with signal processing technique is proposed to achieve the efficient island detection. The robust and optimal power controller with an LMI approach for control of ACmicrogrid is proposed and it explains the centralized control system for power management among the distributed generation sources in grid connected and island mode operation.

1. Introduction:

Nowadays, one of the main goals of utilities is to enhance their networks by various distributed generation (DG) systems with capacities in the range of several kW to hundreds of MW. Distributed Generation (DG) can provide significant benefits, including reduced transmission and distribution costs, reduced emissions, and enhanced reliability. The fuel-cell, wind-turbine, biomass, microturbine, and solar-cellare the sources of distributed generation (DG) system. The island operation is the separation of distributed generation system from the utility grid and operates in island mode to supply the quality power for thecritical load when the grid failure condition. The seamless transition between grid connected mode and island mode, island detection and the control in grid connected mode and island modearethemore challenging tasks for DG system. The use of power converters allows an independent active and reactive power control. In most of the literature, the control of DG power is explained by current and voltage control and the control design algorithm uses observer-based state feedback controller along with PI or modified Repetitive control (MRC). Under current control strategies, the PI controllers find major applications. A PI controller is employed for the grid-connected inverter to command the output current to follow a certain reference current, thus establishing required power transfer to the grid. The PI controllers are generally designed in synchronously rotating reference frame to acquire the benefits of individual control of active and reactive power components of the grid.The LQR method assures robustness but does not allow pole placement in specific regions. Therefore, it may not be possible to use this method to attain both robustness and desired pole placement. Hence, stability analysis, the robustness of a controller and state feedback synthesis via Lyapunov functions can be reduced to a standard convex problem involving LMI algorithms. The stability analysis also the challenging task of the distributed generation system. The efficient islanding detection and immediate disconnection of DGR are critical in order to avoid equipment damage, grid protection interference, and personnel safety hazards. Islanding detection techniques are mainly categorized into remote, local, and signal processing based. These methods are further classified into different techniques on the basis of different parameters, such as detection speed, error detection rate, power quality, non-detection zone (NDZ), and efficacy.

2. Motivation &Problem Definition:

The use of the renewable energy is increasing rapidly at a growing rate. The growth in renewable generation is expected to be 26% of the total generation growth from 2009 to 2035 in U.S, and India aims to increase the amount of electric power from clean energy resources to 40% by 2030 [1]. Therefore, utility companies have already begun to take into account not only the conventional centralized power generation, transmission, and distribution, but also renewable energy-based distributed generations (DGs). With increasing renewable DG, fast and stable mode transition technologies are substantial not only for sending power to the grid but also for protecting DGs from grid fault conditions. Particularly, to supply power to the critical loads under any grid condition has become an important issue [2], because most critical loads are sensitive to voltage variations, which can make the critical load's performance worse or shut down the system operation. One of the attractive features of distributed generation (DG) is the ability to disconnect from the utility grid and continue to supply local loads during grid interruptions. Switching from a grid connected mode to a standalone mode is also known as islanding. It is worth mentioning that if multiple DG units islanded at the same time as a microgrid as shown in Fig. 1, these units must be coordinated to regulate the voltage and frequency and maintain the power balance in the islanded micro grid.Integrating DG sources into the distribution system can also help to electrify rural and isolated areas, and allow supply utilities to provide additional power from nearby DG sources in case of a deficiency of supply from central generation units.

Integration of distributed generation system with large grid does promise higher security and reliability in electricity supply in general. Islanding is a situation in which a distribution system becomes electrically isolated from the remainder of the power system, due to grid fault or any other disturbance, and yet continues to be energized by the DG units connected to it. Apart from improved reliability, islanding operation increases the revenue of DG owner by additional sale.

For the distribution network operators, islanding operation can improve the overall security of power supply and they may also get additional revenue due to the improvement in the quality of supply indices. The control and operation of distributed generation system are the challenging tasks for grid connected and island modes of operation. The control and operation of amicrogridare most challenging task due to complex control of source converters. Without proper control, the reliability and security of distributed generation system can be disrupted.The some of the issues associated with the DG system are as fallows.

i) The voltage and current transients during the connection and disconnection of distributed generation system or disconnection due to asuddenloss of grid power.

ii) The increase of power quality disturbances beyond the level of acceptance for customers especially in harmonic distortion.

iii) Most importantly, DG system may not be able to maintain the voltage and frequency within desired limits in the distribution system when it is islanded.

iv) The protection of the distributed generationa system is a challenging task. The DG systems have to provide enough fault current to operate the protective devices, including circuit breakers, fuses, and fault-protection relays.

v) The Load changes resulting in fast transients that may exceed the capability levels of DG system

vi) One of the most important issues of a DG system is the synchronization of DG system for grid.

vii) One of the major concerns in operating DG systems connected to the grid is the possibility of islanding due to grid disturbances, intentional disconnect for servicing, accidental opening, intentional disconnect from the utility.

To overcome the above issues a seamless transition is needed between grids connected mode and island mode to supply the quality power for the critical load with very less disturbance. The fast-tracking and stable current controller is needed for grid connected mode and island mode operation to achieve the seamless operation of the distributed generation system. The IEEE 1547-2003 and IEC 61727 standardsrequireislanding to be detected and the DG should bedisconnected at most within 2 seconds.The power control and island detection are the challenging tasks for multi DG microgrid system.

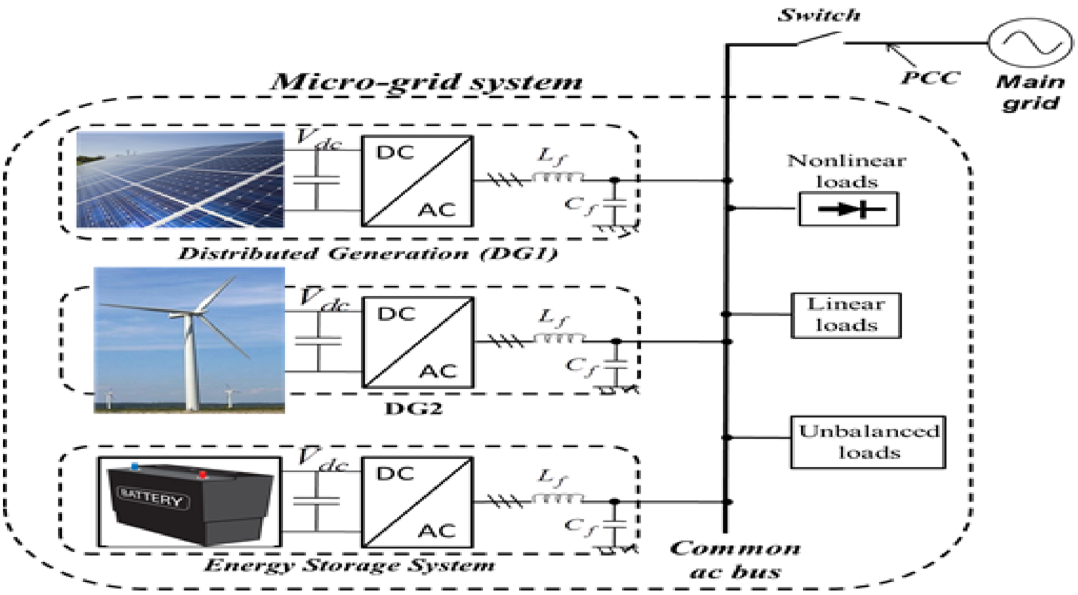

Fig 1. The schematic diagram microgrid

3. **Literature review:**

In the literature of [2]-[4], two categories of critical loads have been discussed. One is the grid-scale power loads requiring very high quality of power including medical equipment, semiconductor industry, and broadcasting facilities. The other is the auxiliary power system to supply AC power to the balance of power plant in renewable or energy storage power systems [5] & [6]. The DC–AC inverter in the current-controlled mode exchanges active and reactive power, which provides continuous power to the critical load. A control algorithm for fault ride through with voltage compensation capability for the critical load is proposed in a three-phase utility-interactive inverter with a critical load [5].

The safeties of themechanical and electrical balance of power plants are very important and considered for critical loads in operating fuel cell power plant systems [6]–[8]. A new voltage sag compensator for powering critical loads in electric distribution systems has been discussed in an AC–AC converter [9]-[10]. Usually, the DG has a DC-AC inverter-based power conditioning system, which is used either to deliver AC power to the grid or load. In [10], during grid connected mode operation, the inverter operates as a current source in or order to deliver preset power to the load and grid, and in island mode operation, the inverter operates as a voltage source to provide constant voltage to the load, and also described an island detection algorithm, intelligent load shedding algorithm, and a synchronization algorithm. A static transfer switch or circuit breaker can be used as the mode switch [11]. The point of common coupling (PCC) switch is another protection switch. If the grid is under fault conditions such as over/under voltage, over/under frequency, etc., then the DG is disconnected from the grid for the protection of the critical load and the DG inverter. If the auxiliary power of the DG inverter control board supplies from the grid as a critical load, the DG inverter should operate in both GC and SA modes to provide uninterrupted and continuous power [12]. Therefore, it is important that the DG inverter controller can detect exact fault conditions and transfer the seamless operational mode within allowable duration to reduce voltage and current spikes. Seamless mode transition methods have been investigated [13]–[24].

A seamless transfer algorithm can switch the inverter operation from the voltage control mode to the current control mode and vice versa with minimum interruption to the local load [19]. The mode switch helps in disconnecting the grid within a half-line cycle. An indirect current control algorithm for seamless transfer of utility-interactive voltage source inverters has been proposed [20], [21]. A seamless transfer of single-phase grid-interactive inverters between GC and SA modes was presented [22]. Four different mode combinations with two switches have been described [23].

A flexible control strategy for an 11-kW wind turbine with a back-to-back power converter capable of working in both SA and GC has been proposed [24]. The proposed control loop consists of a current controller and a feedforward voltage controller, which are to minimize the grid overvoltage (OV). The feedforward voltage control loop is added to the d–q axis current control loop. The proposed control strategy reduces the impact of the renewable energy and the critical load under the grid fault or disturbance conditions. Thetransition between two aforementioned operating modes mayresult in voltage spikes across the local loads and inrushcurrents into the grid due to amismatch in voltage frequency,phase, or amplitude [25]. Therefore, it is important for the DGinverter system to be able to transfer seamlessly betweenoperating modes to reduce voltage and current spikes. In orderto achieve grid synchronization, phase locked-loop (PLL) is commonly used [26]. PLLs are difficult to implement due to their nonlinear property and complex tuning for desired performance [27-29] and it could lead to adverse transient performance with limited distortion rejection capability in non-ideal grid condition [11, 30 12, 31].

The control methods in [27], [29], [32-34] have current and voltage control loops separately for different operating conditions. This increases the complexity and decreases the reliability of the system. Some of these controllers [35-36] only change the voltage reference amplitude, but the phase angle difference is not considered which may cause deviation in grid synchronization when reconnecting to thegrid. Some of these methods [36], [37] suffer from slow transient performance due to the use of nested loop structure and some methods suffers from big voltage spikes and rush grid current during thetransfer process. Furthermore, conventional methods based on cascaded multi-loop control structure in literature are difficult to implement due to their complex tuning. In order to overcome these design challenges. The proposed controller uses just one cost function to achieve the control objectives for all operation modes and thecost function is minimized using LQR optimal control method as in [38]. Islanding functionality requires a control strategy that can detect the loss/availability of the grid and switch between modes, accordingly, with minimal interruption in the voltage across the local load. Seamless transfer between grid connected and islanded modes have been extensively investigated in the literature [40], [10]. The same current control loop used in the grid connected mode is also used in the islanded mode as the internal current loop of the voltage controller. This is proposed to avoid an abrupt transient when switching between control modes. This transient can be noticed in [10]. It is important to emphasize that the transient during the transition from the grid connected mode to the islanded mode can be divided into two parts; the first part occurs when the grid is interrupted and lasts until the islanding is detected. During this period, the unit is still regulating the output current to match a given reference. The second part occurs at the moment when the islanding is confirmed and the control mode is switched from current control to voltage control. Therefore, using the same current loop as in [40] may still result in a noticeable transient in the load voltage if the mismatch is significant between the output current in the grid connected mode and the load current in the islanded mode. An outer voltage control loop is used to generate the current references in the grid connected mode and regulating the load voltage in the islanded mode. The only drawback of this technique is that the output voltage is always regulated at the extreme limit of the allowed voltage range during the standalone operation. Instead of switching between current control and voltage control modes as commonly proposed in the literature of [41], only voltage control is used for both grid connected and islanded modes. In the grid connected mode, the output voltage and frequency of the VSC are used to control the reactive and real power flow, respectively. In other words, droop control or so called integral control is used to inject the required real power into the grid [41], [42]. In the standalone mode, the output voltage and frequency are regulated at their nominal values. Therefore, when the grid is interrupted, the DG unit supplies only the load power autonomously, even before the islanding is detected, due to the use of voltage control. This will achieve a seamless transfer in operation modes without causing any abrupt transient in the load voltage and current, despite transients in the grid current. In the recent past, there is an increase in the distributed power generation due to its low environmental impact and technical advantages [43].

Theuse of power converters allows an independent active and reactive power control. In most of the literature, the control of DG power is explained by current and voltage control and the control design algorithm uses observer-based state feedback controller along with PI or modified Repetitive control (MRC) [43]-[47]&[54]. However, these works did not consider the output feedback error as a state for controller design. Under current control strategies, the PI controllers find major applications. A PI controller is employed for the grid-connected inverter to command the output current to follow a certain reference current, thus establishing required power transfer to the grid [49]. The PI controllers are generally designed in synchronously rotating reference frame to acquire the benefits of individual control of active and reactive power components of the grid [49].The LCL filter designed including resonance damping as in [50]-[52], the control of active and reactive power using PQ theory in grid connected mode and V-f theory island mode were explained in [54]-[56].

The stability androbustness of the system with the controller developed will be investigated using structured singular values or a μ-framework. Specifically, perturbations due to load variations and parameters uncertainties of the system components are considered. A linear quadratic cost function with separate weighting scalars for plant states and servocompensator states have been used to find solutions.The stability robustness and transient response of the resulting control system will be investigated for different choices of these weighting scalars. The transient performance of the system is evaluated by performing moving window RMS calculations of the three-phase output voltages under transient load change from zero to 100% resistive load [57].

The efficient islanding detection and immediate disconnection of DGR are critical in order to avoid equipment damage, grid protection interference, and personnel safety hazards. Islanding detection techniques are mainly classified into remote, passive, active, and hybrid techniques. From these, passive techniques are more advantageous due to lower power quality degradation, lower cost, and widespread usage by power utilities. However, the main limitations of these techniques are that they possess a large on detection zones and require threshold setting. Various signal processing techniques and intelligent classifiers have been used to overcome the limitations of passive islanding [58].

In [59], a dc micro-grid is considered, in which an optimization-based PMS is designed to satisfy the power demand, limit the battery charge current, and set the wind subsystem as the primary resource. In [60] several static converters connect the distributed resources, such as generation and storage systems, to the AC or DC sections of microgrid; also, AC and DC sections are interconnected through further AC/DC converters. Optimization strategies are required to perform the optimal control of the static converters. Such strategies are aimed at efficiently operating the AC microgrid.

4. Research objective:

This research aims at broadly developing new robust control algorithm with stability analysis and island detection algorithm for the DG interface that guarantee stable and supply the quality power for the critical load in grid connected mode, island mode and transition mode of the distributed generation. To be fulfilled, the above objective needs to evolve and builds upon a number of tasks. Key tasks are:

i) Developing the photovoltaic distributed generation system with MPPT and boost converter.

ii) Developing the DG interfacing inverter to act as acurrent source in grid connected mode and voltage source in island mode.

iii) Design LCL filter to attain the pure sinusoidal wave from the distributed generation system.

iv) The design of the full order state observer to estimate the states of the distribution generation system.

v) Design and performance evaluation of robust and optimal controller with an LMI approach to achieve fast tracking and stable control in grid connected and island mode operation of the DG system.

vi) Developing the robust stability analysis of optimal controller for distributed generation system.

vii) Developing the advanced island detection method with signal processing technique.

viii) Developing the robust and optimal power controller with an LMI approach to achieve fast tracking and stable control in grid connected and island mode operation of a microgrid with photovoltaic, battery bank and wind energy sources.

5. Methodology:

The methods explained in the literature for the control of distribution system introduces observer based the conventional PI controller and modified Repetitive control (MRC).However, these works did not consider the robust stability for controller design.

i) Design and performance evaluation of robust and optimal controller with an LMI approach to achieve fast tracking and stable control in grid connected and island mode operation of the DG system.

The robust and optimal controller can be designed using the method which will minimize the cost function. The linear quadratic regulator (LQR)is the best method for optimization of thecost function. The selection of Q and R matrix for LQR is based on trial and error method. It is best practice to select these matrices to be diagonal and the diagonal elements are adjusted such that state variables can be controlled to desired values. Therefore, first select the Q matrix and then select the R matrix which is an identity matrix. More weight is given for diagonal entry for good performance (small rise time and low overshoot). After appropriating good value of Q, the feedback gain matrix (K) is attained using. Any system with only LQR controller has a percentage of error and overshoots which are undesirable. The LQR method assures robustness but does not allow pole placement in specific regions.

Therefore, it may not be possible to use this method to attain both robustness and desired pole placement. Hence, stability, the robustness of a controller and state feedback synthesis via Lyapunov functions can be reduced to a standard convex problem involving LMI algorithms. The various constraints such as Lyapunov and Riccati-inequalities, Linear inequalities, convex quadratic inequalities, matrix norm inequalities can all be written as LMIs.

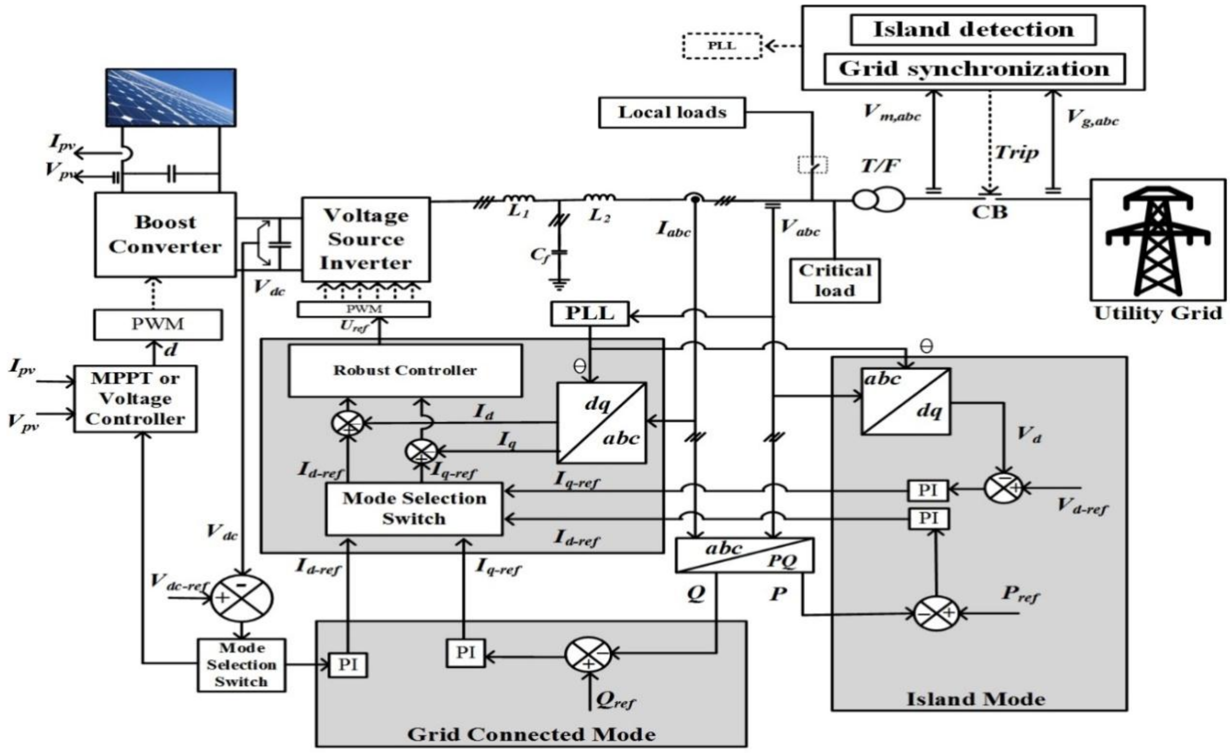

Fig 2. The schematic diagram for control in Grid connected and Islanded mode DG inverter.

Active and Reactive Power Control in Grid Connected Mode: The active power and reactive power from PCC is given as fallows:

$$P = 3/2\,(v_d i_d + v_q i_q)$$

$$Q = 3/2\,(v_q i_d - v_d i_q)$$

Assuming the grid current vector is in phase with grid voltage than the v_q=0. Therefore, the active and reactive power respectively as fallows

$$P = 3/2\,(v_d i_d)$$

$$Q = 3/2\,(-v_d i_q)$$

The current requirement for reactive power compensation is the Ir. The maximum apparent power $|S|=(|v_{a|rms}+|v_{b|rms}+|v_{c|rms)}$ Imax. Where Imax is the maximum current limit then the reference reactive power (Qref) can be expressed as

$$Q_{ref} = |S|I_r$$

Active power and Voltage Control in Island Mode: The active power reference (Pref) is used to generate the Id−ref for the controller. The Pref is given by

$$Pref = |S|(1 - Ir)$$

The q-axis current from the inverter given by

$$Iq = -(v_d wL_L)/(1.5(R_L^2 + (wL_L^2))$$

This suggest that q-axis current of the inverter is proportional to the d-axis voltage.

ii) Developing the robust stability analysis of optimal controller for distributed generation system.

The robust stability analysis of optimal controller for DG system uses the singular value based methods. The stability and robustness of the system and its transient performance can be investigated under various tuning parameters of the controller. The analyses demonstrate that the controller parameters can be tuned and verified to satisfy a certain transient performance requirement and at the same time guarantee robust stability under system parameter uncertainties and load variations.Structured singular value μ can be used to analyze and evaluate the stability robustness of a multi-input multi-output (MIMO) linear system under structured perturbations. In order to use the μ-framework to analyze the robust stability of a linear system under perturbation, the problem needs to be recast into a feedback loop diagram.

iii) Developing the advanced island detection method with signal processing technique.

The passive techniques are more advantageous due to lower power quality degradation, lower cost, and widespread usage by power utilities. However, the main limitations of these techniques are that they possess large Non-detection zone and require threshold setting. Various signal processing techniques and intelligent classifiers have been used to overcome the limitations of passive islanding. The Hilbert transform based island detection is introduced to overcome the limitations of passive detection method in zero power mismatch condition.The positive sequence voltages obtained at the point of common coupling (PCC) and the DGs location are utilized for the detection of islanding situation in the system. The positive sequence voltages are used to islanding detection algorithm based on the Hilbert transform. This technique can efficiently discriminate the system stress conditions from the islanding condition and hence reducing the probability of nuisance tripping of the system.

iv) **Developing the robust and optimal power controller with an LMI approach to achieve fast tracking and stable control in grid connected and island mode operation of a microgrid with photovoltaic, battery bank and wind energy sources.**

The control of a microgrid is acentralized control system (CCS), and the CCS system provides the referencesignalsforthe controller of different distributed inverters of the micro-grid. The robust and optimal power control can be developed for a hybrid ACmicrogrid, where the power flow in the microgrid is supervised based on solving an optimization problem. The optimization of therobust and optimal controller is achieved by using LQR method and this problem can be reduced to a standard convex problem involving LMI algorithms.

6. Research Work Plan (WP):

The design method of robust control is to be verified through various test scenarios to demonstrate the operational capability of the proposed DG system, and the obtained results are to be discussed. The different Island detection techniques need tobe analyzed and aHilbert transform based Island detection technique need to implement using Matlab simulation. The robust control algorithm and island detection algorithm for the DGsystem needs to be developed in the time period of research work plan as follows.

WP1: Developing the photovoltaic distributed generation system with MPPT and boost converter.

WP2**:** Developing the DG interfacing inverter to act as acurrent source in grid connected mode and voltage source in island mode.

WP 3: Design LCL filter to attain the pure sinusoidal wave from the distributed generation system.

WP 4: Design of the full order state observer to estimate the states of the distributed generation system.

WP 5: Design and performance evaluation of robust and optimal controller with an LMI approach to achieve fast tracking and stable control in grid connected and island mode operation of the DG system.

WP 6: Developing the robust stability analysis of optimal controller for DG system.

WP 7: Developing the advanced island detection method with signal processing technique.

WP 8: Developing the robust and optimal power controller with an LMI approach to achieve fast tracking and stable control in grid connected and island mode operation of a microgrid with photovoltaic, battery bank and wind energy sources.

WP 9: Documentation of thesis writing.

Table 1. Time Schedule for the entire work plan:

Sl No	**Activity**	**Time in Months**
1	WP1& WP2	6 months
2	WP3, WP4 &WP5	1 year
3	WP6 ,WP7&WP8	1 year
4	WP9	6 months

Table 2. The Time Schedule for Research Work Plan through bar diagram:

Work Package	1st Year (July-2016 to July-2017)		2nd Year (July-2017 to July-2018)		3rd Year (July-2018 to July-2019)	
WP1						
WP2						
WP3						
WP4						
WP5						
WP6						
WP7						
WP8						
WP9						

7. Conclusion:

The robust and optimal control technique has been introduced for the operation of grid-connected and islanded DG system. The robust and optimal control design is proposed using LQR method with an LMI approach of DG system. The design concept is to be verified through various test scenarios to demonstrate the operational capability of the proposed micro grid.The stability analysis of robust and optimal controller is proposed for DG system in grid connected and island modes of operation. The different Island detection techniques are explained and Hilbert transform based island detection technique is introduced for implementation. The robust and optimal power control strategy for amicrogrid is proposed for implementation in grid connected and island modes of operation.

8. References:

1. G. O. Young, “Synthetic structure of industrial plastics (Book style with annual energy outlook 2011),” With Projections to 2035, DOE/EIA- 0383(2011), Apr. 2011.
2. O. C. Montero-Hernandez and P. N. Enjeti, “Ride-through for critical loads. Exploring a low-cost approach to maintaining continuous connections between buildings and/or industrial systems,” *IEEE Ind. Appl. Mag.*, vol. 8, no. 6, pp. 45–53, Nov./Dec. 2002.
3. M. V. Aware and D. Sutanto, “SMES for protection of distributed critical loads,” *IEEE Trans. Power Del.*, vol. 19, no. 3, pp. 1267–1275, Jul. 2004.
4. S. W. Mohod and M. V. Aware, “Micro wind power generator with battery energy storage for critical load,” *IEEE Syst. J.*, vol. 6, no. 1, pp. 118–125, Mar. 2012.
5. J. Kwon, S. Yoon, H. Kim, and S. Choi, “Fault ride through control with voltage compensation capability for utility interactive inverter with critical load,” in *Proc. IEEE 8th Int. Conf. Power Electron. ECCE Asia*, 2011, pp. 3041–3047.
6. T.-S. Hwang, K.-S. Kim, and B.-K. Kwon, “Control strategy of 600 kW E-BOP for molten carbonate fuel cell generation system,” in *Proc. Int. Conf. Electr. Mach. Syst.*, 2008, pp. 2366–2371.
7. K.-S. Kim, C.-J. Lim, T.-S. Hwang, B.-K. Kwon, J.-S. Kim, C.-H. Choi, and S.-G. Choi, “A 600KW electrical balance of plant with LCL filter for molten carbonate fuel cell,” in *Proc. 13th Eur. Conf. Power Electron. Appl.*, 2009, pp. 1–7.
8. T.-S. Hwang, H.-S. Heo, and K.-S. Kim, “High performance synchronization algorithm for 600 kW EBOP of fuel cell generation system,” in *Proc. IEEE Int. Conf. Ind. Technol.*, 2010, pp. 1195–1200.
9. E. C. Aeloiza, P. N. Enjeti, L. A. Moran, O. C. Montero-Hernandez, and S. Kim, “Analysis and design of a new voltage sag compensator for critical loads in electrical power distribution systems,” *IEEE Trans. Ind. Electron.*, vol. 39, no. 4, pp. 1143–1150, Jul./Aug. 2003.
10. I.J. Balaguer, Q. Lei, S. Yang, U. Supatti, and F. Z. Peng, “Control for grid-connected and intentional islanding operations of distributed power generation,” *IEEE Trans. Ind. Electron.*, vol. 58, no. 1, pp. 147–157, Jan 2011.
11. B. Mirafzal, M. Saghaleini, and A. Kaviani, “An SVPWM-based switching pattern for stand-alone and grid- connected three-phase single-stage boost inverters,” *IEEE Trans. Power Electron.*, vol. 26, no. 4, pp. 1102– 1111, Apr. 2011.
12. J. Kwon, S. Yoon, and S. Choi, “Indirect current control for seamless transfer of three-phase utility interactive inverters,” *IEEE Trans. Power Electron*, vol. 27, no. 2, pp. 773–781, Feb. 2012.
13. Z. Yao, Z. Wang, L. Xiao, and Y. Yan, “A novel control strategy for grid interactive inverter in grid-connected and stand-alone modes,” in *Proc. 21st Annu. IEEE Appl. Power Electron. Conf. Expo.*, 2006, pp. 19–23.
14. Z. Yang, H. Liao, C. Wu, and H. Xu, “Analysis and selection of switch for double modes inverter in micro-grid system,” in *Proc. Int. Conf. Elect. Mach. Syst.*, 2009, pp. 1778–1781.

15. S. Huang, L. Kong, and H. Xu, “Control algorithm research on seamless transfer for distributed resource with a LCL filter,” in *Proc. 3rd Int. Conf. Electric Utility Deregulation Restruct. Power Technol.*, 2008, pp. 2810– 2814.
16. M. N. Arafat, S. Palle, Y. Sozer, and I. Husain, “Transition control strategy between standalone and grid-connected operations of voltage-source inverters,” *IEEE Trans. Ind. Appl.*, vol. 48, no. 5, pp. 1516–1525, Sep./Oct. 2012.
17. G. Shen, D. Xu, and D. Xi, “Novel seamless transfer strategies for fuel cell inverters from grid-tied mode to off-grid mode,” in *Proc. 20th Annu. IEEE Appl. Power Electron. Conf. Expo.*, 2005, vol. 1, pp. 109–113.
18. Z. Liu and J. Liu, “Seamless transfer strategy with outer current loop for three phase inverter in distributed generation,” in *Proc. IEEE Energy Convers. Congr. Expo.*, 2010, pp. 3556–3560.
19. R. Tirumala, N. Mohan, and C. Henze, “Seamless transfer of grid connected PWM inverters between utility-interactive and stand-alone modes,” in *Proc. 17th Annu. IEEE Appl. Power Electron. Conf. Expo.*, 2002, pp. 1081–1086.
20. J. Kwon, S. Yoon, and S. Choi, “Indirect current control for seamless transfer of three-phase utility interactive inverters,” *IEEE Trans. Power Electron.*, vol. 27, no. 2, pp. 773–781, Feb. 2012.
21. H. Kim, T. Yu, and S. Choi, “Indirect current control algorithm for utility interactive inverters in distributed generation systems,” *IEEE Trans. Power Electron.*, vol. 23, no. 3, pp. 1342–1347, May 2008.
22. Z. Yao, L. Xiao, and Y. Yan, “Seamless transfer of single-phase grid interactive inverters between grid-connected and stand-alone modes,” *IEEE Trans. Power Electron.*, vol. 250, no. 6, pp. 1597–1603, Jun. 2010.
23. X. Wang, C. Zhang, X. Li, and Z. Guo, “Weighted control research on seamless transfer for dual-mode three phase inverter in micro-grid,” in *Proc. Int. Conf. Elect. Mach. Syst.*, Aug. 20–23, 2011, pp. 1–5.
24. R. Teodorescu and F. Blaabjerg, “Flexible control of small wind turbines with grid failure detection operating in stand-alone and grid-connected mode,” *IEEE Trans. Power Electron.*, vol. 19, no. 5, pp. 1323–1332, Sep. 2004.
25. M. Rizo, M. Liserre, E. Bueno, F. J. Rodriguez, and C. Giron, “Voltage Control Architectures for the Universal Operation of DPGS,” *IEEE Trans. on Ind. Informatics,* vol. 11, pp. 313-321, 2015.
26. “IEEE Application Guide for IEEE Std 1547(TM), IEEE Standard for Interconnecting Distributed Resources with Electric Power Systems,” *IEEE Std 1547.2-2008*, pp. 1-217, 2009.
27. Rodri, x, P. guez, A. Luna, Mu, “A Stationary Reference Frame Grid Synchronization System for Three-Phase Grid-Connected Power Converters under Adverse Grid Conditions,” *IEEE Trans. On Power Elec.*, vol. 27, pp. 99-112, 2012.

28. P. Rodriguez, J. Pou, J. Bergas, J. I. Candela, R. P. Burgos, and D. Boroyevich, "Decoupled Double Synchronous Reference Frame PLL for Power Converters Control," *IEEE Trans. on Power Elec.*, vol. 22, pp. 584-592, 2007.
29. X Li, H Zhang and R S. Balog, "Control strategy for seamless transfer between island and grid-connected operation for a dual-mode photovoltaic inverter," *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2015, pp.5983-5990.
30. T. Thanh-Vu, C. Tae-Won, L. Hong-Hee, K. Heung-Geun, and N. Eui- Cheol, "PLL-Based Seamless Transfer Control Between Grid-Connected and Islanding Modes in Grid-Connected Inverters," *IEEE Trans. On Power Elec.*, vol. 29, pp. 5218-5228, 2014.
31. G. Xiaoqiang, L. Wenzhao, Z. Xue, S. Xiaofeng, L. Zhigang, and J. M. Guerrero, "Flexible Control Strategy for Grid-Connected Inverter Under Unbalanced Grid Faults Without PLL," *IEEE Trans. on Power Elec.*, vol. 30, pp. 1773-1778, 2015.
32. X Li and R. S. Balog, "PLL-less robust active and reactive power controller for single phase grid-connected inverter with LCL filter," *IEEE App. Pow. Elec. Conf. and Expo. (APEC)*, 2015, pp. 2154-2159.
33. L. Qin, Y. Shuitao, and F. Z. Peng, "Multi-loop control algorithms for seamless transition of grid-connected inverter," *IEEE Applied Power Electronics Conference and Exposition (APEC)*, 2010, pp. 844-848.
34. H. Shang-Hung, K. Chun-Yi, L. Tzung-Lin, and J. M. Guerrero, "Droop controlled inverters with seamless transition between islanding and grid connected operations," *IEEE Energy Conv. Cong. and Expo. (ECCE)*, 2011, pp. 2196-2201.
35. D. S. Ochs, B. Mirafzal, and P. Sotoodeh, "A Method of Seamless Transitions Between Grid-Tied and Stand-Alone Modes of Operation for Utility-Interactive Three-Phase Inverters," *IEEE Trans. on Ind. App.*, vol. 50, pp. 1934-1941, 2014.
36. Z. Qing-Chang and T. Hornik, "Cascaded Current-Voltage Control to Improve the Power Quality for a Grid-Connected Inverter With a Local Load," *IEEE Trans. on Ind. Elec.*, vol. 60, pp. 1344-1355, 2013.
37. G. Bin, J. Dominic, Z. Jingyao, Z. Lanhua, C. Baifeng, and L. Jih-Sheng, "Control of electrolyte-free micro inverter with improved MPPT Performance and grid current quality," *IEEE App. Pow. Elec. Conf. and Expo. (APEC)*, 2014, pp. 1788-1792.
38. C. Olalla, R. Leyva, A. El Aroudi and I. Queinnec, "Robust LQR Control for PWM Converters: An LMI Approach," in *IEEE Transactions on Industrial Electronics*, vol. 56, no.7, pp.2548-2558, July2009. doi: 10.1109/TIE.2009.2017556.
39. M. A. Zamani, T. Sidhu, and A. Yazdani, "Investigations into the control and protection of an existing distribution network to operate as a microgrid: A case study," IEEE Trans. Ind. Electron., vol. PP, no. 99, pp. 1–1, 2013.

40. C. T. Rodrıguez, D. V. de la Fuente, G. Garcer´a, E. Figueres, and J. A. G. Moreno, “Reconfigurable control scheme for a PV micro inverter working in both grid-connected and islanded modes,” IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 1582–1595, Apr. 2013.
41. M. Dai, M. N. Marwali, J.-W. Jung, and A. Keyhani, “Power flow control of a single distributed generation unit,” IEEE Trans. Power Electron., vol. 23, no. 1, pp. 343–352, Jan. 2008.
42. E. A. A. Coelho, P. C. Cortizo, and P. F. D. Garcia, “Small signal stability for single phase inverter connected to a stiff AC system,” in IEEE 34th Industry Application Conf., 1999, pp. 2180 – 2187.
43. A. F. Q. Gonalves, C. R. Aguiar, R. F. Bastos, G. G. Pozzebon and R. Q. Machado, Voltage and power control used to stabilize the distributed generation system for stand-alone or grid-connectedoperation, in IET Power Electronics, vol. 9, no. 3, pp. 491-501, 3 9 2016. doi: 10.1049/ietpel.2015.0071.
44. C. Dirscherl, J. Fessler, C. M. Hackl and H. Ipach, State-feedback controller and observer design for grid-connected voltage source power converters with LCL-filter, IEEE Conference on Control Applications (CCA), Sydney, NSW, 2015, pp. 215-22.
45. Lan Zhou, Jinhua She, Shaown, and Qiwei Chen, H∞ Controller Design for an Observer-Based Modified Repetitive-Control System InternatinalJournel of Engineering Mathematics Volume 2014, doi:10.1155/2014/838905
46. T. Hornik and Q. C. Zhong, “H-infinite repetitive current controller for gridconnected inverters”,35th Annual Conference of IEEE Industrial Electronics, Porto, 2009, pp.554-559. doi: 10.1109/IECON.2009.5414981.
47. J. Kukkola and M. Hinkkanen, Observer-Based State-Space Current Control for a Three-Phase Grid-Connected Converter Equipped With an LCL Filter, in IEEE Transactions on Industry Applications, vol. 50, no. 4, pp. 2700-2709, July-Aug. 2014.
48. Ma Liang and Trillion Q. Zheng, ”Synchronous PI control for three phase grid connected Photovoltaic inverter,” in Chinese Control and Decision Conference(CCDC), 2010, pp. 2302 2307.
49. Allal M. Bouzid, P. Sicard, A. Chriti,M. Bouhamida and M. Benghanem, Structured H∞ design method of PI controller for grid feeding connected voltage source inverter,in 3rd International Conference on Control, Engineering Information Technology (CEIT), 2015 , pp. 1 6.
50. R. N. Beres, X. Wang, M. Liserre, F. Blaabjerg and C. L. Bak, A Review of Passive Power Filters for Three-Phase Grid-Connected Voltage-Source Converters, in IEEE Journal of Emerging and Selected Topics in Power Electronics, vol. 4, no. 1, pp. 54-69, March 2016.
51. M. Liserre, F. Blaabjerg and S. Hansen, Design and control of an LCL-filter-based three-phase active rectifier, in IEEE Transactions on Industry Applications, vol. 41, no. 5, pp. 1281-1291,Sept.-Oct.2005. doi: 10.1109/TIA.2005.853373.

52. A. Reznik, M. G. Simes, A. Al-Durra and S. M. Muyeen, Filter Design and Performance Analysis for Grid-Interconnected Systems, in IEEE Transactions on Industry Applications, vol. 50, no. 2, pp. 1225-1232, March-April 2014.
53. Egea-Alvarez, A.; Junyent-Ferr, A.; Gomis-Bellmunt O, Active and reactive power control of grid connected distributed generation systems. In Proceedings of Modeling and Control of Sustainable Power Systems, pp. 4781 (2012).
54. Zhang Chun, Ma Qishuang, Cui Tongkai and Zhang Poming, Modelpredictive current control of DC/AC inverters with time delay compensation, in IEEE International Conference on Aircraft Utility Systems (AUS), 2016, pp. 398 402.
55. L. Liu, H. Li, Y. Xue and W. Liu, Decoupled Active and Reactive Power Control for Large-Scale Grid-Connected Photovoltaic Systems Using Cascaded Modular Multilevel Converters, in IEEE Transactions on Power Electronics, vol. 30, no. 1, pp. 176-187, Jan. 2015. doi: 10.1109/TPEL.2014.2304966.
56. A. Kahrobaeian and Y. A. R. I. Mohamed, Interactive Distributed Generation Interfacefor Flexible Micro-Grid Operation in Smart Distribution Systems, in IEEETransactionson Sustainable Energy,vol.3, no.2,pp.295- 305,April 2012.doi:10.1109/TSTE.2011.2178045.
57. M. N. Marwali, Min Dai and A. Keyhani, “Robust stability analysis of voltage and current control for distributed generation systems,” in *IEEE Transactions on Energy Conversion*, vol. 21, no. 2, pp. 516-526, June2006.doi: 10.1109/TEC.2005.860406.
58. S. Raza, H. Mokhlis, H. Arof, J. Laghari, and L. Wang, "Application of signal processing techniques for islanding detection of distributed generation in distribution network: A review," Energy Conversion and Management, vol. 96, pp. 613-624, 2015.
59. W. Qi, J. Liu, and P. D. Christofides, “Distributed supervisory predictive control of distributed wind and solar energy systems,” IEEE Trans. Control Syst. Technol., vol. 21, no. 2, pp. 504–512, Mar. 2013.
60. P.T. Baboli, M. Shahparasti, M.P. Moghaddam, M.R. Haghifam, M. Mohamadian, “Energy management and operation modeling of hybrid AC-DC microgrid,” IET Generation, Transmission & Distribution, vol. 8, no. 10, pp. 1700-1711, 2014.