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Assessment of Novel Metrics for Different VSI Control Strategies in a Micro-Grid

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Abstract

Interest in the integration of renewable energy with utility network and Distributed Generation (DG) using inverters is on the rise. The parallel operation of inverters must be studied closely for achieving better power quality. Issues in controlling these parallel connected inverters to a micro-grid have been brought to focus in this paper. This paper defines metrics for comparing the various control strategies for grid-connected inverters. Ten such control strategies are taken up and evaluated against the proposed eight metrics. The results of the comparison are presented in this paper.

Keywords: Control Strategy, Metrics, Model Predictive Control, Parallel Inverter

1. Introduction

Sustainable energy sources are Renewable Energy Sources (RES) as these energies are generated from inexhaustible green energy sources such as solar, wind, water, and others. These sustainable energy sources spread across the consumer locality and the generators generating power from them are rightly known as Distributed Generation (DG) systems. DGs are bidirectional i.e. even consumers can export power to the grid. One can import power from the grid during lack of renewable source and can export surplus energy produced locally to the grid. This minimizes transmission power loss unlike the conventional transmission methods were power generated remotely has to travel long distance to reach the users above all power produced is clean and environment-friendly.

Inverter plays a major role in facilitating these DGs power to the end-users in terms of safety and quality. As power flows in either direction, safety is the main concern and in a micro-grid environment there will be multiple power sources injecting power to the grid through inverters affects the quality of the grid power[1–5]. These Multiple inverter systems connected to a common AC grid, essentially operate in parallel and they must be controlled for stable system operation and to prevent overloading of the individual inverter. Inverters are operated in parallel because of the diversity in generation systems and its geographical spread of the sites of operation. The active and reactive power flow between DGs and the bus are shown.

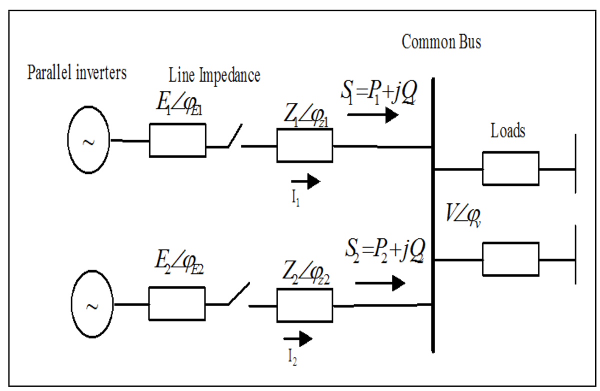

Figure 1. Equivalent circuit of parallel-inverters-based microgrid.

$E_1 < \varphi_{E1}$ is voltage and power angle of 1st inverter, $E_2 < \varphi_{E2}$ is voltage and power angle 2nd inverter, $Z_1 < \varphi_{z1}$ is impedance of the first inverter system, $Z_2 < \varphi_{z2}$ is impedance of the 2nd inverter system, $V < \varphi_v$ is bus voltage and power angle, $S_1=P_1+jQ_1$ is apparent power by first inverter, $S_2=P_2+jQ_2$ is apparent power by 2nd inverter, I_1 is current fed to bus by first inverter, I_2 is current fed to bus by second inverter. Three phase Voltage Source Inverters (VSI) is controlled by two strategies mainly current control and voltage con-

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trol. Phase angle difference of inverter output voltage and the grid voltage is used to control power flow in voltage controlled VSI. Modulation techniques like Pulse Width Modulation (PWM) etc. are used to control the active and reactive components of current injected into the grid[6–7].

There are a variety of control strategies available, such as a conventional droop control method, H-infinity control method, model predictive control method and few other methods[9–10] however, a comprehensive comparison of all the available control methods of the inverters is not available in the literature. In this work, the comparison of control is done with the help of carefully chosen metrics such as power quality, fault tolerance, communication dependency[11], modularity, sensor inputs, easy implementation and computational complexity. Such a comparison of all the available grid-tied inverters is not available in the literature.

2. Metrics for Performance Evaluation

Parallel operating inverters in a distributed system should have proportional current sharing between inverters. Further, the output should have the same voltage amplitude, frequency, and phase. Furthermore, flexibility to increase the number of units required should be possible and plug and play capability is mandatory for expansion. The parallel operation of inverters has advantages of better thermal management, reliability, redundancy, modularity, maintainability and size reduction. The description of each of the chosen metrics is presented below:

2.1 Power Quality

Grid voltage distortions could be expected frequently, hence injecting a clean and safe balanced current is important. Harmonic distortions produced in the grid due to non-linear load will reflect at the sources which in turn deteriorate power converter components and other devices in the system[13,14]. Total harmonic distortion is generally given as

$$THD = \sqrt{\frac{P_2 + P_3 + P_4 + \ldots .. + P_n}{P_1}} \times 100\% \qquad (1)$$

THD is total Harmonic Distortion

P_1, P_2, P_3… are power at various instances. The inverter's output impedance influences THD reduction. Control strategies that can change the output impedance from being inductive to resistive and capacitive, could bring down THD considerably[14,15]. THD is one of the fore-most metrics for deciding upon the controller's suitability for parallel operating power converters.

2.2 Fault Tolerance

The Power Grid encounters a lot of uncertainties. Faults can occur at any magnitude and at any time. Design and implementation of the fault detection and fault tolerant controller are mandatory. One of the integral parts of the micro-grid management is the diagnosis and control of faults. In case of occurrence of any fault in the system, the micro-grid must be disconnected from the main grid, avoiding further propagation and a fast reconnection after fault rectification is essential. Fault ride-through capability is also necessary[16]. Fault tolerance capability is one of the most desirable metrics for controllers of grid-connected parallel inverters.

2.3 Robustness

Robust design ensures to retain the system performance despite model inaccuracies and changes, while the system is subjected to various disturbances[17]. This is a very desirable trait for the controllers of parallel connected inverters.

2.4 Communication Dependency

A controller could be very smart and efficient with good communication infrastructure. A good and capable controller should do its objective without communication dependency. Communication infrastructure along with a power infrastructure will always impose interference in both the circuits. Thus it is better to operate both circuits separately else independently without depending on one another[12–19]. Thus here in our proposed system if the communication dependency is reduced or made unnecessary that will be an apt controller.

2.5 Easiness in Expanding

Easy expandability can also be termed as modularity of the system. If the system expands i.e. loads and service connections keep on increasing and the system should manage it smoothly. There should not be any complications in adding any extra inverter to the system to meet the load demand. The controller which easily adds an inverter into the system is very much needed these days[20,21]. So, modularity or expandability plays an important role in choosing a controller for parallel operation of inverters.

2.6 Switching Islanded / Grid Connected

Smooth and seamless switching between stand-alone and grid-connected mode is more welcomed for a micro-grid. The controller in our application should facilitate this transfer of operation mode easily. The power quality maintained during the stand-alone mode should not be affected during the grid integration and vice versa.

2.7 Easiness in Implementing

Controllers should be simple easy and cost effective for implementing them in various scenarios. Fabrication and implementation should be practically feasible for any proposed controller. Those controllers should with stand and perform well in most of the environmental and industrial adverse conditions. Thus, simple and reliable implementing capability for a controller is an important metric for comparing the controller suitability.

2.8 Computational Complexity

Computation time of the processor involved in controller implementation must be checked or else the response time of the controller will be huge which is undesirable for a good controller. The control processor should not consume much time in evaluating control algorithm. Difficult, complex and large math steps make people less interested with a controller and burdens them in designing and implementing. This obviously makes people to shift to a simple controller compromising some functionalities even though they are very important. More and more equations and loops in control algorithms will increase computation time which should be as less as possible for the system to perform efficiently and respond promptly and accurately. The control processor should not have complex steps which are time-consuming for finishing the operation. Thus, computation complexity is an important factor while choosing an apt controller.

The next section presents a brief overview of the various controllers that are compared using the chosen metrics.

3. Control Strategies for Comparison

Controllers generally can be classified into two main groups 1) Linear controllers and 2) Nonlinear controller[22]. PI controller (stationary, synchronous.), proportional–resonant, predictive deadbeat controllers, State feedback controllers, are some of the linear controllers[4]. Hysteresis, Ramp comparison, Delta Modulation (DM), Sliding mode control, Neural Networks, Fuzzy-logic based Controllers and on-line optimized controllers are some of the nonlinear controllers[12–23].

3.1 Proportional-integral Controller

The most commonly used classical PI controller is very simple and is used in many power electronic applications. PI controllers show poor performance with unbalanced systems. This controller must deal with positive and negative sequence currents separately in an unbalanced system. These controllers are very effective with linear time-invariant SISO systems. For a balanced system PI controller designed and formulated in the d-q frame will be a better solution[24,25]. Whereas, PI controller designed in synchronously rotating reference frame need prompt information of grid voltage and are complex in implementing as they require two coordinate transformations[26]. The performance of this controller gets affected when the system condition changes and, they are inefficient in handling higher order harmonic disturbances.

The PI controller is the most common control algorithm used for current error compensation. A PI controller calculates an error value as the difference between a measured inverter output current and a desired injected current to the grid, then the controller attempts to minimize the error between them[8,27]. The proportional term K_p of the controller is formed by multiplying the error signal by a K_p gain. This tends to reduce the overall error with time. However, the effect of the proportional term will not reduce the error to zero, and there is some steady state error. The Integral term K_i of the controller is used to fix small steady-state errors[8,17]. The Integral term integrates the error then multiplies it by a K_i constant and becomes the integral output term of the PI controller. This removes the steady state error and accelerates the movement of the process to the reference point.

The PI current control offers an excellent steady-state response, low current ripple, constant switching frequency, in addition to well-defined harmonic content. Moreover, the controller is insensitive to system parameters since the algorithm does not need system models. PI controllers can be applied either in the stationary (αβ) or in synchronous (dq) reference frame. When the synchronous PI controller is used, the control variables become DC and the PI compensators are able to reduce the stationary error of the fundamental component to zero[24]. This is not the case with PI controllers working in the stationary system, where there is an inherent tracking error of phase and amplitude. Therefore, current control in a synchronous (rotating) reference frame, using PI controllers is the typical solution in the three-phase grid-connected inverters.

3.2 Proportional Resonant Controller

The PR controller deals only with sinusoidal signals, and designing with correct gain is a challenge even for a skilful designer for maintaining performance at the fundamental frequency and at the same time to reject harmonics. These controllers exhibit good performance when designed in αβ or abc-frame[28]. They could regulate the grid power by tracking sinusoidal reference current and eliminating the considerable steady-state error. Proportional and resonant term together known as PR these controllers are widely used in inverter control as they eliminate steady-state error effectively[29–31]. PR controller along with a harmonic compensator will reduce considerable grid current distortions. This controller works well if system frequency and the resonant frequency are maintained very close.

3.3 Hysteresis Controller

This simple Hysteresis current controller is easy to implement for inverter control. This controller immediately senses the error signal and gives control signal to the inverter directly. The current is controlled within a narrow band, which has an upper and lower band limit. The output ramps up and down inside this hysteresis bandwidth. The required signal is maintained to stay within the limits by turning OFF the top switch and turning ON the bottom switch of a leg corresponding to a phase of the inverter when the output current touches or crosses the upper limit[32–34]. Else if the output current touches or crosses the lower limit, the bottom switch is turned OFF and the top switch is turned ON.

The harmonic performance is not good; however, it can be improved by varying the width of the hysteresis band. When the width of the hysteresis band has reduced the switching, the frequency will increase but harmonic performance could be improved. The inductor and the DC voltage applied to the inductor by the inverter also influence the switching frequency.

3.4 Sliding Mode Controller

Sliding Mode control (SM)[16] is a nonlinear robust control, which alters the dynamics of a nonlinear system. Here a discontinuous control signal forces the system to "slide" along a cross-section of an uncertain system's normal behaviour. In sliding mode control chattering is one of the worst obstacles which is due to the high gain control actions and switching imperfections. Especially chattering in the control input will result in system instability and excite high-frequency dynamics phenomenon in the system[15]. The control input is compared with the Pulse Width Modulation (PWM) ramp voltage and generates the appropriate switching pattern of the inverter.

3.5 Droop Controller

This technique is a popular controller for Parallel grid-connected inverters. For inverters with resistive type output impedances, the real power output of the inverter is proportional to the grid voltage E and the reactive power is proportional to the load angle. If the output impedance is inductive then the reactive power is proportional to grid voltage and real power is proportional to load angle. The typical characteristic of the droop control is shown in Figures 2(a) and 2(b). Output impedance plays a major role in the quality of the power injected by the inverter. For resistive output impedance, the effect of frequency is nullified and the effect of nonlinear loads are considerably checked which will help in improving the THD. n_i and m_i are the droop coefficients i.e. slopes of the droop characteristics. E^* is the inverter output voltage and ω^* is inverter output frequency. This droop controller in spite of all its advantages the proportional sharing among the parallel inverters remains a challenge for both linear and nonlinear loads, especially the reactive power sharing accuracy can't be achieved satisfactorily.

Transient response of the system is slow with droop controllers and it is tough to improve the transient response without compromising the power-sharing.

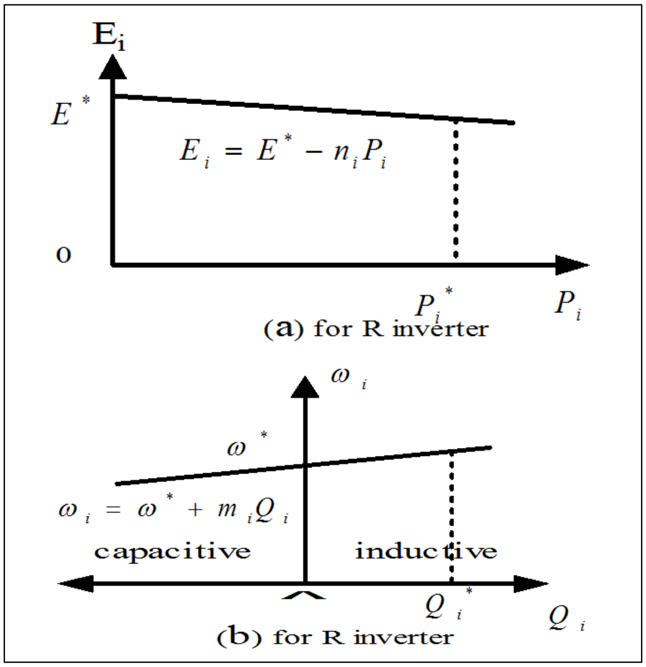

Figure 2. Droop control strategies for resistive output impedance.

3.6 Deadbeat Controller

Deadbeat (DB) controllers are suitable for current controllers because of their fast-dynamic response. These controllers are very sensitive to system uncertainties. These controllers come under predictive controllers as they minimize the error forecasted in the event of tracking the reference current. In inverters, these controllers could track sinusoidal currents efficiently in the absence of nonlinear loads. The main drawback of these controllers is its efficiency in reducing harmonic distortions introduced by nonlinear loads. Parameter variations are also sensed immediately because of fast dynamic behaviour. It requires a good filter model to get the desired performance. However, in low sampling frequency applications, these controllers are suitable as they have a very fast transient response with low harmonic distortions.

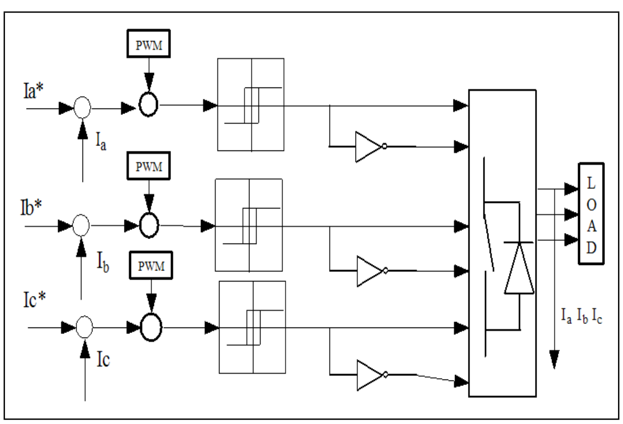

Figure 3. Block diagram of ramp comparison controlled.

3.7 Artificial Neural network

There are many neural networks already proposed and yet to be proposed however the three things which remain common are neuron, architecture and learning algorithm. Artificial Neural Networks (ANN) are model-free estimators i.e. if a system doesn't have an accurate mathematical model or if a system doesn't have a model at all, then ANNs or Fuzzy Logics(FZ) methods can be used for estimating the output signal from an input signal. Among the various ANNs feedforward, ANN is the famous one. Neural networks are trained by optimizing the criterion function which requires numerous iterations. Gradient descent method of training is the most efficient and back propagation classifier is the most popular technique. These techniques take more time to converge but are simple to understand.

3.8 H-Infinity Controller

H infinity controller is one of the important robust controllers applied nowadays in voltage restorer, DC-DC boost converters, UPSs, active power filters and grid-connected power electronics. Controller K(s) is stabilized to maintain H-infinity gain less than one. peak gain inside and outside the control bandwidth respectively.

One can achieve good tracking performance and stability with this method. A small value of around 0.1 is assigned to the weight on the controller transfer function this will ensure that the D12 matrix of the augmented plant is of full rank. However, in designing H∞ loop-shaping involve, selecting the weighting functions and reducing the order of K(s) without affecting the performance as the original controller[18].

3.9 Model Predictive Controller

MPC is a controller used extremely in process industries. The receding-horizon principle is the basis for the model predictive controller[10,35]. MPC acts as a single controller which selects the possible state that minimizes the cost function of the system model. These calculations are made in the discrete environment.

Control horizon is maintained same for all the inverters, thereby giving equal weight for each inverter module connected. Now one can write a cost function easily.

For the parallel-inverter system, the multivariable predictive controllers require many tuning parameters, namely, a prediction horizon N_y for each of the output variables and a control horizon N_u for each of the input variables, as well as performance weights for each output and input.

3.10 Ramp comparison control

This controller produces sine-triangle PWM where the modulating function is the current error. If the current error ≥ triangular waveform, inverter leg is switched in the positive direction. If the current error ≤ triangular waveform, inverter leg is switched in the negative direction. In this method, the considerable amount of harmonics is produced current error will cross the ramp signal frequently. This will result in the line current errors such as magnitude error and phase error. These errors can be compensated or reduced by adjusting the controller gain. Ramp comparison control for the three-phase inverter is shown in Figure 3.

4. Comparison of Control Strategies

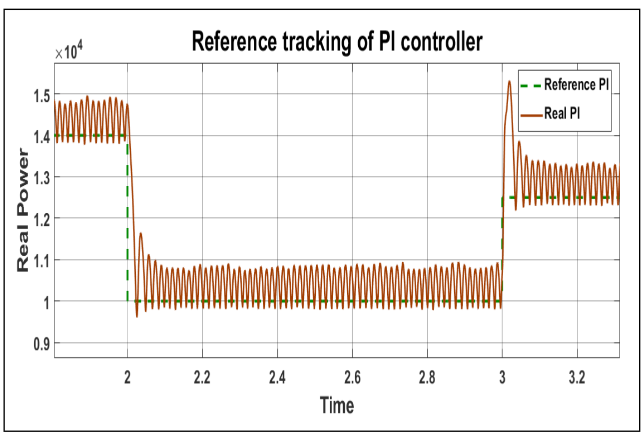

Figure 4. reference tracking of pi controller.

Table 1 presents for the first time in the literature, the comparison of the eight control strategies against the eight-metrics chosen and analysed in this work. It can be found from the Table 1, that PI and PR controllers are simple and have less computation complexity. Hence for a low-cost grid-connected system, such a controller can be preferred.

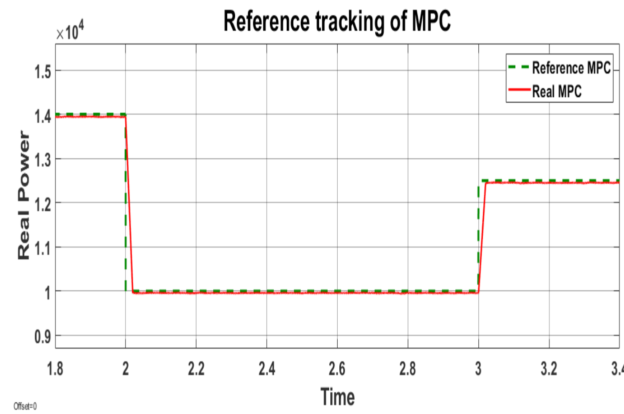

Figure 5. Reference tracking of MPC controller.

Droop control can be employed in a geographically spread area, where communication between inverter units are not easily established. The sliding mode controller has conceptual and computation complexity and implementing them for grid-connected inverters in real time have a certain drawback such as poor reliability. But sliding mode controllers can assure considerable THD reduction compared to other controllers and have enough fault tolerance capability. When power quality and fault handling capability is the prime necessity then sliding mode, the controller serves well with considerable communication requirements as they need the momentary status of each inverter modules connected to the main grid. Robust controllers such as H infinity, predictive deadbeat, and MPC can reduce THD considerably and assure good power quality. Their response to the grid faults and other such disturbances is also reasonably good. But designing and implementing them constitutes challenges. If designing and computing capability is not a constraint in real time application, then these controllers could be a better choice. Two controllers namely PI controller and MPC controller is simulated for a voltage source inverter. The current waveform of these controllers is shown in the Figures 4 and 5. the reference tracking capability of the MPC controller is more accurate than the widely used PI controller.

5. Conclusion

The paper has proposed a metrics for comparing the performance of various controllers for grid-connected inverters. The salient features of each of the controller have also been presented. It has been found that pre-

Table 1. Comparison of controllers for grid-connected inverters

	Metrics for Performance Evaluation of Grid Connected Inverter Systems							
	Power quality	Fault-tolerant	Robustness	Communication Dependency	Easiness in expanding	Switching Islanded/Grid	Easiness in Implementing	Computation complexity
PI	Low	Yes	Yes	Yes	Yes	No	High	Low
PR	High	Yes	Yes	No	Yes	Yes	High	Low
Hysteresis	Low	Yes	Yes	Yes	Yes	Yes	High	Low
SM	High	Yes	Yes	Yes	Yes	Yes	Low	High
Droop	Medium	Yes	Yes	No	Yes	Yes	High	Low
Deadbeat	High	Yes	Yes	No	Yes	Yes	Medium	Medium
ANN	Medium	Yes	Yes	No	Yes	No	Medium	Medium
H infinity	High	Yes	Yes	No	Yes	Yes	Low	High
MPC	High	Yes	Yes	No	Yes	Yes	Medium	Medium
Ramp	Medium	Yes	Yes	No	Yes	Yes	High	Low

dictive deadbeat and MPC controllers show excellent performance during nonlinear load conditions and has good power-sharing capabilities. MPC also has hot-swap operations which brings out the robustness of these control schemes. Hence, in-terms of power quality and computational complexity model predictive controller clearly outperform the other controllers. However, the sliding mode controller has better fault handling capacity. If simplicity is the requirement, then PI controller can be preferred. It has been established in this paper that the proposed metrics helps researchers in advancing further in the research of grid-connected parallel operated inverters.

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