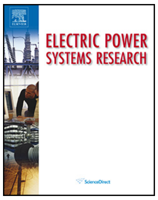
Electric Power Systems Research 151 (2017) 359–368

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr



Grid interconnection of renewable energy sources using multifunctional grid-interactive converters: A fuzzy logic based approach

Vigneysh T., N. Kumarappan*

Department of Electrical Engineering, Faculty of Engineering Technology, Annamalai University, Annamalai Nagar, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 28 February 2017
Received in revised form 9 June 2017
Accepted 12 June 2017

Keywords:
Distributed generation (DG)
Adaptive fuzzy PI controller (AFPI)
Fuzzy logic control (FLC)
Grid-interactive converter (GIC)
Power quality (PQ)

ABSTRACT

This paper proposes a multi-objective control strategy using adaptive fuzzy PI (AFPI) controller for grid-interactive converter (GIC). The proposed controller utilizes the robust and adaptive nature of fuzzy logic control (FLC) and simple structure of PI controller to effectively improve the dynamic performance of the GIC during uncertainties. In the proposed method, the gains of the PI controller are dynamically adjusted by the fuzzy logic based supervisory control system according to the system operating conditions. Hence, it provides fast dynamic response with reduced overshoot and settling time during disturbances. In addition, the proposed Takagi–Sugeno (TS) fuzzy model is computationally more effective when compared to mamdani type fuzzy models. In the proposed multi-objective control scheme, the GIC is utilized to provide various ancillary services in addition to its primary function of injecting active power to the grid. Computer simulation shows that the dynamic performance of the proposed controller is robust than the conventional PI controller during disturbances. Additionally, the results are compared with the existing literature to validate the performance of the proposed controller.

1. Introduction

With ever increasing energy demand and due to various environmental concerns, the present day power system is moving into a new paradigm with high penetration of renewable energy sources (RES) integrated to the distribution network by means of distributed generation (DG) [1,2]. Normally, the DG units are connected in parallel with the utility grid through grid-interactive converters (GIC). Its primary function is to inject the available active power to the grid at unity power factor. However due to various factors such as intermittent nature of RESs and due to market price considerations, DG units may not continuously supply the rated active power to the grid. Thus, the rating of the converters is underutilized most of the time. Hence the unused apparent power rating of the GIC can be used to provide various ancillary services in addition to its primary function [3,4].

On the other hand, high penetration of power electronic interfaced DG units to the distribution network and proliferation of various non-linear loads deteriorates the power quality (PQ). Further, the sensitive and critical local loads supplied by the DG units are also susceptible to various PQ problems. As a result of poor PQ, the on-grid electricity price will be affected in the PQ sensitive markets [5]. Therefore, it is essential to implement proper control technique to integrate DG units to the utility grid to transfer high quality current to the grid with low total harmonic distortion (THD) as per the IEEE standards [6].

In literatures [7–28], various control methods are proposed to interface the RES based DG units to the utility grid. The PQ of the utility grid is ensured either by using additional compensating devices or with the help of GIC with multifunctional capabilities [7–11]. The use of additional compensating device to mitigate the PQ problem increases the system cost and it may not be economical as far as low voltage distribution side is considered. Hence to overcome this issue, recently, GIC with multifunctional capabilities is proposed to provide various ancillary services in addition to its primary function of injecting active power to the grid [12].

As the PQ mainly depends on the output current, current controlled voltage source converter (VSC) are generally used to interface the DG units to the grid point of common coupling (PCC) [13,14]. The current control techniques based on proportional-resonant (PR) controller, proportional-integral (PI) controller and hysteresis controller are most widely used current controllers to control GIC's [15–21]. Each and every current control techniques

---

* Corresponding author.
E-mail addresses: vigneysh@live.com (T. Vigneysh), kumarappann@gmail.com (N. Kumarappan).

http://dx.doi.org/10.1016/j.epsr.2017.06.010
0378-7796/© 2017 Elsevier B.V. All rights reserved.

has own merits and demerits. For example in Refs. [15–17], PR controllers are used to control the GIC in stationary reference ($\alpha\beta$) frame. When compared to PI controller, as PR controller provides high gain at the resonant frequency and offers zero steady error. However, the performance is limited by bandwidth of the system. Hence, the harmonic compensators of PR controllers are effective in controlling lower order harmonics only. Similarly, the hysteresis controllers have certain advantages such as simple and robust structure. It offers quick response in tracking the reference values. However, due to its variable switching frequency, it produces high ripples in the output current along with high switching losses and it causes difficulties in designing the output filter [18,19]. The traditional linear controllers like fixed gain PI/PID controller in synchronously rotating (*dq0*) frame are also widely reported in literatures to control GIC [7–9,11–14,20–21]. The PI controller is easy to implement due to its simple structure and offers good performance while tracking the reference values in *dq0* frame. However its main drawback is, the performance is suffered due to system parameter variations and hence it offers poor transient response when the operating point of the GIC varies. Hence the performance of the fixed gain PI/PID controllers are limited to determined operating points [22,23]. To address the operating point issues, different variations for PI controller is reported in literature (such as addition of grid voltage feed-forward path, multi-state feedback control etc.). Generally, it helps to increase the bandwidth of PI controller. However, it will push the system towards their stability limits [17]. In short, the lack of intelligence or non-adaptive nature of PI, PID or PR controller has encouraged the researchers to apply the intelligent techniques such as fuzzy logic, evolutionary algorithms and neural networks for controlling GICs [24–28].

Fuzzy logic control (FLC) is a popular non-linear and adaptive control technique, which provides robust performance during parameter uncertainties [29]. In Ref. [26], mamdani type fuzzy model is used to control the single phase GIC and the authors have not discussed about the multi-functional capability of GIC. Similarly, in Refs. [27,28], mamdani type fuzzy model is used to control the GIC. The mamdani type fuzzy model is computationally more complex and difficult to optimize. Also, it involves lot of mathematical calculations when compared to the Takagi–Sugeno (TS) based fuzzy model as considered here. In Ref. [28], the authors have used seven membership functions to define each control input and totally 49 rules are used for voltage controller. As a result, it naturally invokes more computational burden. Similarly, the authors have not discussed about the multi-functional features of the GIC.

As different from previous publications, in this paper, adaptive fuzzy PI (AFPI) controller is proposed to control the GIC with multi-functional capabilities. Here, the TS based fuzzy model is proposed to design the AFPI controller. The TS fuzzy model has an outstanding feature, that is, the combination of the fuzzy rule and the form of the exact linear function. Therefore, it is easy to compute and optimize and hence computationally more effective than mamdani type fuzzy model [30]. The proposed AFPI controller consists of TS based fuzzy supervisory control system (FSCS) at its upper level and a simple PI controller at its lower level. If there are any changes in the system operating conditions, the FSCS quickly detects them and dynamically adjusts the PI controller gains. Thus, the supervisory control system forces the controller to work in a linear region for a wide range of operating conditions and consequently, the dynamic response of the system is improved with reduced overshoot, oscillations and with fast settling time. Additionally, in the proposed multi-objective control strategy, the GIC is controlled to provide various ancillary services in addition to its primary function of injecting active power to the grid at unity power factor. It is assumed that there is enough apparent power is available to achieve the following ancillary services simultaneously: i) compensating non-linear load current harmonics, ii) compensating load reactive power demand, iii) compensating unbalanced load current and neutral current. All these objectives are achieved with less number of membership functions and less number of rules and hence the computational burden is significantly reduced when compared to mamdani type models. The whole system is simulated using Matlab package. To validate the effectiveness of the proposed controller, necessary results are compared with the existing literature.

2. System description

Fig. 1 shows the schematic diagram of the DG interfaced to a 3-phase 4-wire distribution network through multi-functional GIC. A three phase, three-leg, two level VSC is used here. The RES based DG unit is connected to the dc-link through a power conditioning unit (PCU). The dc-link capacitor (C_{dc1} and C_{dc2}) decouples the RES based DG units from the utility grid and permits independent control of converter on both side of the dc-link [4]. The output of the GIC is connected to the utility grid through a LCL filter. A damping resistor, R_d is connected in series with the filter capacitor, C_f to provide passive damping and to damp out resonances. Various balanced/unbalanced linear/non-linear local loads are connected to the PCC.

2.1. Reference current extraction

The primary objective of the proposed multi-objective control strategy is to inject the available active power from DG units to the utility grid. While satisfying the primary objective, the GIC is simultaneously controlled to provide the following ancillary services: i) compensating load reactive power demand, ii) compensating non-linear load current harmonics, iii) compensating unbalanced and neutral current, so as to keep the grid current balanced and sinusoidal under all the operating conditions with low THD as per IEEE standards [6]. If the available output from DG is zero, then the GIC will acts as an active power filter and provides only the ancillary services. In order to fulfill the above said objectives, appropriate reference current has to be extracted.

The reference current for GIC is extracted based on the sensed load current, GIC output current and dc-link voltage (V_{dc}) as shown in Fig. 2. All the control algorithms are implemented in *dq*0 frame [12]. The reference angle (θ) for *dq*0 transformation is provided by the enhanced phase locked loop (EPLL) and the details can be found in literature [32]. The error between V_{dc} and its reference (V_{dc}^*) is used to regulate the output active current of the DG units (i_{DG}^*). Since, the secondary function of GIC is to provide harmonic compensation, the harmonic components of the non-linear load current (i_{ldh}) is extracted using low pass filter (LPF) and used as a reference current for the GIC. It is then added with i_{DG}^* to form the *d-axis* reference current (i_{cd}^*) for the GIC. Therefore i_{cd}^* carries the information regarding the active current that needs to be injected from the DG units to the grid and also the current reference to compensate the non-linear load current harmonics and it is given by Eq. (1).

$$i_{cd}^* = i_{DG}^* + i_{ldh} \tag{1}$$

The *q-axis* component (i_{lq}) of the load current represents the reactive demanded by the load and so it is directly utilized to compensate the entire load reactive power demand. Hence the *q-axis* reference current for the GIC can be defined as in Eq. (2). Similarly, the *0-axis* component is responsible to compensate the neutral/unbalanced load current. Therefore the *0-axis* reference current for the GIC is set as Eq. (2),

$$i_{cq}^* = i_{lq}; \quad i_{c0}^* = i_{l0} \tag{2}$$