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A novel adaptive fuzzy membership function tuning algorithm for robust control of a PV-based Dynamic Voltage Restorer (DVR)

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ABSTRACT

In this paper, a novel method to simultaneously tune the antecedent and consequent membership functions of an adaptive observer-based indirect fuzzy controller, is presented. Using the proposed computationally-light algorithm, the membership functions are dynamically tuned while the state variables and the nonlinearities of the system are estimated based on the plant's operation point. Moreover, perturbations are estimated using Lyapunov's principles along with stabilizing terms to achieve fast and robust performance. As a result, the proposed approach can be used to control systems with unknown state variables, state functions and control gains. In this regard, controlling the output of a PV[1]-based DVR[2] system to mitigate various power quality problems is presented as the main case-study in this paper. Moreover, to aid the DVR when acting as a FCL[3] device, a new approach in state variable selection is proposed. Based on the simulation results performed using the MATLAB-SIMULINK environment, superior performance of the proposed observer-based scheme over various cases of conventionally-tuned controllers are observed. The proposed approach also shows superior performance over conventional variable selection methods, specifically when dealing with power quality issues with current nature, such as downstream load-side short circuits.

1. Introduction

Recently, due to the increasing number of sensitive loads and the losses caused by the power-quality problems, the aspect of power quality has attracted the attention of many researchers. These losses can be categorized as loss of production, reduction in life of the load equipment, improper operation of protective devices and energy metering problems along with deviation of the supervisory equipment such as variable speed drives from desired performance (Sundarabalan and Selvi, 2015). In this regard, upstream faults, excitation of large magnetizing inductances such as those utilized in large motors or large transformers and sudden load variations are known as the main causes of power quality fluctuations. Voltage sags, swells, unbalanced loads and harmonic distortions can be named as the most important power quality fluctuations.

To preserve the quality of the transmitted power, various devices such as D-STATCOM[4], DVR, SVC[5] and UPQC, best known as CPDs[6] are widely used. Among the mentioned CPDs, the DVR has proven to be the most cost efficient solution (Kanjiya et al., 2013). By injecting an appropriate series voltage, most common power quality issues such as voltage sags and voltage swells can easily be mitigated using the DVR.

Apart from voltage sag/swell, unbalanced voltages and overcurrents caused by load-side short circuit faults could also be considered as important power quality issues. The ability to limit the effect of these faults is known as FCL functionality (Fereidouni et al., 2013). Conventional FCL devices operate in normal mode in absence of downstream short-circuit faults. This results in decreased efficiency in energy conversion and equipment utilization. Their performance might even cause unbalanced voltages due to short-circuiting the faulty phase. On the other hand, considering the DVR as a series CPD, it could be utilized to minimize the effects of downstream short-circuit faults. Recent researches on FCL-DVRs show increase in the overall rating of the DVR, resulting in higher

Abbreviations: DVR, Dynamic Voltage Restorer; FCL, Fault Current Limiting; CPD, Custom Power-Electronic Device; VCFC, Voltage-Current Fault Compensating; MKY, Meyer-Kalman-Yakubovich; SPR, Strict Positive Real; MIMO, Multy-Input Multy-Output; RMS, Root Mean Square; THD, Total Harmonic Distortion; max, min, Maximum, Minimum; PV, Photovoltaic; MPP, Maximum Power Point; MPPT, Maximum Power Point Tracking; OP, Operation Point; $D_{i(j)}$, Duty Cycle of The $I^{th}(J^{th})$ System; IAE, Integral of Absolute Error (IT; T_R, Rising Time; T_S, Settling Time; PCC, Point of Common Coupling

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[1] Photovoltaic.
[2] Dynamic Voltage Restorer.
[3] Fault Current Limiting.
[4] Distributed Static Compensator.
[5] Static VAR Compensator.
[6] Custom Power-Electronic Devices.

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system cost. Yet, it would be a great merit for a system to mitigate voltage type power quality fluctuations (such as sag/swell and higher order harmonics) and current type power quality fluctuations (such as over-currents and unbalanced phase voltages) with a single device. From this point forward, this type of device is referred to as the VCFC[7] device throughout this paper.

In this regard, the contribution of this paper covers two aspects. The first aspect is improving the performance of the DVR acting as a VCFC-DVR by using a new state variable selection. Therefore, to minimize the mentioned drawbacks of the VCFC-DVR system, a novel approach has been proposed and utilized in this paper. In this novel approach, the load current is used as the main system state variable instead of the conventional load voltage error. Thus, the same structure can be used to compensate both fault types, eliminating the need for higher rated systems. On the other hand, the same controller (control principles) which is used to mitigate voltage fluctuations is utilized to maintain the load current at desired values or limit the short circuit fault effects at all instances, leading to lower system complexity and lighter calculation burden. This supervisory controller is the second aspect considered in this paper.

Among various common nonlinear control schemes, the fuzzy control approach, due to the ability to utilize simple linguistic terms, model highly nonlinear systems with unknown dynamics and online adaptability has been focused on by many researchers (Barkat et al., 2011; Brandizzi et al., 1999; Ling et al., 2016; Mandal et al.,.2015; Marouf et al.,. 2016; Ngo and Shin, 2015; Santos et al., 1996). The Fuzzy-logic can be applied to the system in two ways, namely, direct and indirect approaches. In the direct approach, the control signal is directly generated by the fuzzy controller; while in the latter, the capability of the fuzzy-based controller to estimate smooth nonlinear functions over a compact set is used (Wang, 1994). Hence, based on these estimations, the control signal is generated.

Employing indirect fuzzy control to estimate various systems has been studied in many researches (Boulkroune, 2015; Li et al., 2015). In these controllers, to guarantee desirable closed loop operation, despite various types of uncertainties and disturbances, the control structure has to be tuned based on the operation point. In this regard, various methods have been studied to tune the structure of the fuzzy controller. Most of these methods use offline approaches to tune the fuzzy parameters. Because of the time consuming training process required in these approaches, these type of tuning methods are not applicable for adaptive systems where the input–output have to be processed real-time (Park and Cho, 2004).

Conventional online tuning of fuzzy parameters has been considered in (Boulkroune, 2015; Liu and Tong, 2015; Moradi et al., 2012) by researchers. The efforts made in these researches, due to impractical simplifying assumptions are not applicable to realistic systems. In some of these researches, the control gain used in the state equations is considered to be known prior to controller design (Barkat et al., 2011; Moradi et al., 2012); in some other researches, although the control gain is considered as an unknown function, the sign of the gain is considered to be known (Park et al., 2005). Considering the control gain as an unknown constant is another impractical assumption, common in many researches (Liu et al., 2011). Similarly, these assumptions as pointed out in (Boulkroune and M'saad, 2012), are impractical and unrealistic.

Although adaptive online tuning schemes examined in (Liu et al., 2011; Pan and Er, 2013; Ranjbar-Sahraei et al., 2012) contain interesting results, the assumptions of availability and measurability of the state variables at all times, limits their implementations to theoretical applications. In practice, plants are generally unknown and the only signals available are the control input and the system output signals. As a result, observer-based controllers attracted the attention of many researchers.

In (Leu et al., 2005, 1999; Tong et al., 2004), controlling processes using adaptive observer-based fuzzy schemes have been investigated. In most of these approaches, the MKY[8] method is used to examine the stability of the system. In using the MKY method, the estimation and observation errors have to exhibit SPR[9] *d*ynamics. Therefore, the dynamics of the main error, not meeting SPR conditions are augmented by a low-pass filter designed to satisfy the SPR condition of a transfer function associated with the Lyapunov stability analysis (Boulkroune and M'saad, 2012). As a result of this filtering, large dynamic order is exhibited by the observer controller (Park et al., 2005). Moreover, the sign of the control gain is considered to be known, where, as mentioned before, is an impractical assumption (Ye, 2001).

Since designing an adaptive observer-based self-tuned fuzzy controller with unknown control gain is a very challenging task, it has been addressed out in very few researches (Boulkroune and M'saad, 2012; Liu et al., 2011). In (Boulkroune and M'saad, 2012), a method to optimally tune observer-based fuzzy controllers with unknown control gain is proposed. Interesting results are expressed in this work. Yet, as pointed out by Boulkroune and M'saad (2012), due to the employed filtering and the existing filtering terms in the control signal, design of the control system is very hard. Hence, to ease and simplify the design procedure, the control gain has been considered to exhibit very slow varying dynamics (i. e. Constant gain). Similarly, in (Liu et al., 2011). In (Boulkroune and M'saad, 2012), the fuzzy functions are filtered and the control gain is considered as a constant. These assumptions, even in the case of solving the problem of the employed filtering, will limit the application of the presented approaches to certain examples. Hard implementation, need for stronger ICs with higher sampling rate and limited applicability to certain examples can be named as the drawbacks of these schemes presented.

The mutual drawback of all the mentioned schemes is that the antecedent membership functions have to be tuned by the designer prior to controller design. The task of designing static antecedent membership functions, besides demanding time consuming training procedures, might also need high design experiences. Moreover, various static forms taken by the membership functions affect the closed loop control dynamics in different ways, where some force the controller to deviate from desired characteristics. It will be shown that dynamically and simultaneously modifying the antecedent and consequent membership functions will improve the closed loop control behavior compared to the case where at least of set of membership functions are static predefined membership functions. There has never been an approach to simultaneously tune the membership functions, online, using a simple computationally light algorithm. Therefore, in this paper, to overcome the mentioned drawbacks, an observer-based indirect adaptive fuzzy controller, tuned using a novel parameter and membership function tuning method is proposed. The proposed approach is used to control MIMO[10] systems where the control gain, the state functions, the state variables and the disturbance/uncertainty terms are considered unknown.

In the proposed method, unlike the approaches presented in (Barkat et al., 2011; Moradi et al., 2012), *t*he magnitude and sign of the control gain are considered to be unknown. Moreover, in the indirect fuzzy controller, the function estimations and parameter tunings are performed using online simple computationally-light

[7] Voltage-Current Fault Compensating.

[8] Meyer-Kalman-Yakubovich.

[9] Strict Positive Real.

[10] Multi-Input Multi-Output.