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Comparative Analysis of Controller Techniques Used in Doubly Fed Induction Generators in Wind Turbines

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ABSTRACT

The interest in the variable speed wind turbines has increased due to their very attractive features. The fundamental feature of the DFIG is that the power processed by the power converter is only a fraction of the total wind turbine power, and therefore its size, cost, and losses are much smaller compared to a full-scale power converter. The aim of the control strategy is usually to maximize the output power, maximize the efficiency of energy conversion besides minimizing output power oscillations or minimizing wear of the mechanical components of the power plant, e.g., train drives while maximizing the economic profit. Many different topologies have been proposed to achieve the desired speed control on wind generators. Among the various controllers considered based on classical control theory like PI controllers and nonlinear controllers based on the Fuzzy logic PI controller using Fuzzy logic, Heuristic algorithm, Genetic Algorithm, Swarm optimization and Sliding Mode controllers were compared. It has been observed that among various controllers the fully fuzzy scheme was best in terms of stabilization times and reduction in asymmetries. However from the tuning of PI controller the swarm optimization technique is best suited for optimizing the parameters of the controller.

Keywords: *WECS, DFIG, PI, WT, FRT, GA, Fuzzy.*

1. INTRODUCTION

In case of remote, rural areas general generation using wind energy generation is quite common. The unbalanced voltages, under-voltage or over-voltage conditions result in weak, unbalanced power transmission grids [9]. A number of problems like overheating, stress on mechanical components due to pulsations in torque occur when the stator voltages are unbalanced. The wind turbines are unconnected from the grid for their own protection, resulting in a significant impact on their energy production. Among all variable speed wind turbine concepts, the concept with doubly-fed induction generator (DFIG) provides an attractive option. It is becoming the most popular choice for wind turbines due to its ability to control the rotor currents thereby allowing variable speed operation resulting in its operation at maximum efficiency over wide range of wind speeds. The power required is only 25-30 percent of the total power for attaining full control of the induction generator (IG) connected to the grid through the stator terminals and the rotor terminals are connected to the grid via a partial-load variable frequency AC-DC-AC converter (VFC) and transformer. Both active and reactive power control of the generator is decoupled along with improved energy production, better power quality, and improvement in dynamic performance when power system disturbances occur. The problems caused by unbalanced stator voltages can be controlled by the rotor currents which allow for adjustable speed operation and reactive power control. Issues related to weak rural grids can be addressed by developing a control method. An important

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challenge faced by the wind power industry is to improve the fault ride-through (FRT) capability of doubly fed induction generators (DFIGs) in wind power applications [5].

For a wind power plant, one of the most important features which characterize the overall design is control of the rotational speed of the electric machines coupled to wind generators. The efficiency of conversion of wind energy into mechanical energy for a given value of the speed of the wind, geometry of blades and orientation of turbine is determined by the speed of the wind. This mechanical energy is then transformed into electric energy by the generator driven by the wind turbine.

2. DFIG MODEL

The squirrel cage induction generator model is very similar to the mathematical model of DFIG having one difference between them i.e. in case of DFIG, the rotor windings are not short-circuited and therefore the rotor voltage is not zero as in the case of squirrel cage induction generator. In case of doubly fed induction generators (DFIGs) improvement in the fault ride-through (FRT) capability for wind power applications is one of the crucial challenges faced by the wind power industry. The mathematical models of such generators enable us to analyze their response under generic conditions but their mathematical complexity does not contribute to simplifying the analysis of the system under transient conditions and hence does not help in finding straightforward solutions for enhancing their FRT[5].

A DFIG model is classically a fifth-order system model which needs to be simplified so as to accurately estimate the behaviour of the system and at the same resulting in significant reduction in its complexity. The operation of DFIG WT is satisfactory when the grid is operating under balanced conditions but its performance deteriorates when the network is unbalanced or voltage sags affect the voltage at the point of common coupling (PCC)[5]. Due to electromagnetic transient of the DFIG high overcurrent's occur in the converter under such conditions due to which the converter needs to be disconnected to prevent damage to the semiconductors.

Different solutions for enhancing the fault ride-through (FRT) capability of DFIG WTs under transient conditions have been published. The solutions were based on implementing advanced features on the existing rotor and grid side converters. A reliable study of the performance of generator is helpful for finding a reliable solution. The fifth-order model of DFIG based WTs has extensively been used to study its behavior under generic conditions, as demonstrated in [5]. However, this kind of model gives rise to a complicated system that does not enable carrying out a simple analytical study of the DFIG under transient conditions. To overcome these problems, a simplified third-order model was presented in [5]. This proposal simplifies the fifth-order model by neglecting the stator electric transients. However, the unbalanced effects in the network voltage are not taken into account, as demonstrated in [5]. Due to these features, this model is not valid for studying the FRT in DFIGs.

3. CONVERTER MODEL

The model of the converter system includes the representation of the rotor-side converter, the grid-side converter and dc link and the converter control. The rotor-side converter (C1) and grid-side converter (C2) are modeled as a voltage source.

4. TYPES OF CONTROLLERS

One of the important features which characterize the overall design of wind power plant is the control of the rotational speed of the electric machines coupled to a wind generator. The conversion efficiency from mechanical to electrical energy is determined by given wind speed, the geometry of the blades and orientation of the turbine. Maximizing output power is one of the aims of the control so that the conversion efficiency is maximum. Other objectives like reducing power output oscillations, wearing of the mechanical components of the power plant, and increasing the profit can also be defined. Many different topologies have been proposed to achieve the desired speed control on wind generators [7].

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The cost, suitability, and reliability of a topology depend upon the type of electric machine and the complexity of the additional electronic devices needed. Doubly fed asynchronous generators are becoming a popular alternative when the wide range variable speed operation is needed. Many different control algorithms have been developed for this topology where the aim is to control the power drawn from the wind and limit the power in case of high wind speeds besides controlling the reactive power. In case of a wind turbine, the dynamics of the electrical and mechanical systems are having different time responses i.e. electrical dynamics is more rapid than the mechanical dynamics. In an overall control system, two control levels i.e. DIFG control level and wind turbine control level are used being strongly connected to each other. DFIG control level having a small time constant due to fast acting electrical control independently controls the active and reactive power of the wind turbine whereas wind turbine control level supervises pitch control system and contains turbine control itself.

5. COMPARISON OF TYPES OF CONTROLLER

Both linear controllers which are based on classical control theory like the proportional-integral controller and nonlinear controllers based on fuzzy theory have been used . In the majority of the cases the linear controllers have been widely used but in some papers, PID controller has also been used. In this paper the performance of a controller for DIFG model based on classical control theory has been compared with the combination of PI controller along with the Fuzzy controller, the PI controller using heuristic algorithm, the PI controller using Genetic Algorithm (GA), PI controller using swarm optimization and PI controller using sliding mode controller has been evaluated.

5.1 Classic PI Controller

The DFIG control containing two controllers- one for rotor side converter and the other for grid side converter was being used. The rotor side converter independently controlled the reactive and active power indirectly by controlling the rotor current. The inner control loop regulates the active and reactive component whereas the outer loop defines the current set point [3]. The D.C. voltage and reactive power were controlled indirectly by controlling the current of grid side converter. The speed of the generator was limited due to the physical restrictions on wind turbine related to size and efficiency of the generator. Two cross-coupled controllers - one for speed and the other for power limitation using vector control were used for tracking the optimum operating point of the wind turbine. This helped in limiting the power between the grid and wind turbine (WT) generator in case of high speed winds. This method of control [3] was designed for a normal continuous operation which allowed the turbine to operate with optimum power efficiency over a wider range of wind speeds. However, in this case, the capability of the DFIG to handle grid faults and enhancement of controller capabilities was not investigated. Also, the present controller's performance with variable speed (variable pitch) having a focus on voltage and frequency regulation on the grid needs to be evaluated. The strategies used for control of variable speed wind turbine using DFIG was implemented using power system tool DIgSILENT [3].

5.2 PI controller with Fuzzy Control

Three different control topologies were applied:

- Linear controller
- Non-linear controller
- Mixed scheme combining both linear and non-linear controllers

A proportional and integral (PI) controller based on classical control theory was used as a linear controller and fuzzy controller used as a non-linear controller. The linear control system used two nested PI control loops with the inner loop acting on applied voltages to windings of the rotor. The second control loop was a speed controller which took samples of the stator current so as to keep waveform and phase shift at specified values. The Ziegler Nichol’s (ZN) method was used to tune the parameters of PI controller. The fuzzy controller was designed using

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four input variables and 75 linguistic rules to provide slip and current control for inner loop [7]. The tuning of non-linear controllers was achieved through trial and error type simulations.

In the case of the mixed scheme, the fuzzy controller was used as a supervisory control over the PI controller. In this scheme, the parameters of the PI controller were dynamically adjusted by the fuzzy controller which was based on 6 input variables and 100 linguistic rules. The performance of three control methods was compared in terms of settling time and steady state error of speed. These methods were also compared in terms of reduction in asymmetries in case of uncontrolled currents. None of the control methods showed any steady state slip error.

The PI control reduced settling time and asymmetries by 0.0017%, fuzzy control by 0.00022% and mixed scheme by 0.0015% [7]. The fully fuzzy scheme was found to be best in terms of stabilization time and reduction in asymmetries. The advantages of this controller are limited due to a lot of development time and information required for the tuning of the controller. This requires a deep knowledge of the system as to what would be the response to external stimuli. The drawback of fuzzy controller is that the performance of the controller is very crucial to the accuracy of this information.

In case of a fuzzy supervised scheme, the performance of the linear controller is improved slightly but it has two major advantages which make it preferable to both linear controller and only fully fuzzy controller. These controllers can be easily tuned even if we do not have any reliable knowledge as well as the transient and dynamic responses of the system as compared to the fully fuzzy controller [7]. The linear controller is generally designed for a particular working point as we assume the system model to be linear but due to its non-linearity, the fuzzy supervised PI controller can be designed to operate the system at different working points without any degradation in the response. The linear controllers have fast and easy methods available for tuning a good controller but their disadvantage is that have low flexibility with regards to operation at several working points and high sensitivity to changes in the system.

5.3 PI Controller using Heuristic Algorithm

An algorithm based on the improvisation method used by the musicians called HS algorithm has been used widely [1] due to its advantages that in this case no initial settings are required for control variables with few mathematical operations and no derivatives are required. In basic HS algorithm [1] we call each solution "harmony" which is represented by an n-dimensional real vector. A randomly generated initial population of harmony is stored in a harmony memory (HM). The algorithm has three basic stages - initialization, improvisation of harmony vector and updating of HM. The GHS algorithm uses dynamic updating method besides generating new harmony vector by using best harmony vector.[1] Another algorithm SGHS (self-adaptive GHS) used four control parameters HMS, HMCR, PAR and BW which are closely related to the problem whose solution is desired. The search process maybe explorative or exploitative.

Bees colony algorithm (BCA) proposed in [1] simulates the intelligent method of searching used by bees for food. It is a stochastic optimization algorithm based on three groups of bees - employed bees, onlookers, and scouts in a colony of artificial bees.[1] Simulated annealing algorithm (SAA) is based on a metallurgy technique which involves heating and controlled cooling of a material which increases the size of its crystals simultaneously reducing their defects [1].

In this case, each solution in search space is considered equivalent to physical system state and internal energy minimization is defined as the objective function of that state. The PI controller was tuned using ZN tuning by setting "I" (integral) gain to zero and "P" (proportional) gain was increased from zero till it reached ultimate gain at which output of control loop oscillates with constant amplitude. The control loop frequency responses were investigated using Bode dig. The gains of PI controller were tuned using SGHS, SAA, BCA and ZN algorithms in an autonomous WECS with a PMSG connected to DC converter [1] for reducing tracking error and percent overshoot. SGHS required less time for optimization and provided parameters with most optimal performance. The performance of current controller loop was almost same with PI parameters obtained using

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any one of SGHS, SAA, and BCA algorithms although SGHS is slightly better. SAA gave better performance and less error in case of values obtained for speed loop controller.

5.4 PI Controller using Genetic Algorithm

The proportional and integral (PI) controllers have been conventionally used for DFIG control as they provide robust performance and simple structure. The proper choice of PI gains affects the system performance and success of PI controller. The use of genetic algorithm (GA) for designing controllers in electrical systems was cited in [10] with focus on improving system stability.

The PI controller using GA has been compared with PI controller obtained using trial and error design with the objective of reduction in overcurrent in rotor circuit and improving dynamic damping performance [10]. GA is an optimization and search tool based on methods same as natural selection in genetics. The GA method consists of an initial population which comprises of a set of possible solutions for the problem coded in the form of chromosomes. Three genetic operators - selection, crossover, and mutation are applied to these initial chromosomes. The possible solution of a problem is represented by a chromosome such that each set or set of bits represents a value assigned to some variables of the problem. A fitness function is defined which plays the role of environment in the natural process [10]. The GA was implemented with an initial population of 100 and for obtaining the optimal solution the generations used were 100. The GA based PI controller was capable of reducing overcurrent in rotor circuit during the transient period and also increased the margin of transient stability as well as overall DFIG time domain performance.

5.5 PI Controller using Swarm Optimization

The non-linear components in power system can be easily controlled by using various modern control techniques such as intelligent control, adaptive control etc. but some of these control techniques have few real applications due to their complicated structures or because of stability issues [6]. Thus conventional PI controllers due to their simple structure are most commonly used [6]. However tuning a PI controller is very monotonous and it is quite difficult to tune PI gains properly due to non-linearity and complexity of the system. In the past years trial and error based algorithms like GA, SA has been used for power system stabilizers (PSS) design [6]. The performance of these trial and error algorithms degrades when the parameters which are to be optimized using these algorithms are interdependent [6].

Particle swarm optimization (PSO) is a new technique which is being successfully used for single and multi-objective non-linear optimization [6]. PSO has been used for automatic voltage controller (AVC) of a conventional turbo generator [6] based on step-response. The transient response of the controller has not been investigated. The objective of controller used on grid side is to keep d.c. link voltage constant irrespective of rotor power flow. Particle swarm optimization is based on the pattern of group flight congregation of birds where we search for an optimal solution. A solution is represented by a particle which occupies a position in problem space. A swarm of particles moves through the problem space with each particle keeping a track of its individual best position. In this method, first a population of particles occupying random position is initialized and a fitness measure is defined for evaluating each particle's performance. The present position of the particle is compared with the position based on the fitness function. The best position is updated for individual particle and compared with the best position of the whole swarm. Then velocity of the particle is updated and on this basis, each particle changes its position. This is repeated until good fitness or maximum no. of iterations is achieved.

The final value of swarm position is regarded as the optimal solution. Five particles were used in the simulation. The first particle was initialized with initial parameters using the relationship

$$2(xgbest\ k) - xi(k)) \quad i = 1.2. \ldots\ldots, N \quad - (1)$$

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The other four particles were initialized with values around the parameters designed using eq. (1). The weighted factors in (3) were chosen as α = 0, β = 1 so as to limit the current in rotor circuit during a fault. The PSO was implemented with 30 trial runs by applying a 100 ms 3 phase short circuit at receiving the end of line 2 [6]. The PSO helped in obtaining optimal parameters of PI controllers and improved the transient response of the system over a wide range of operating conditions.

5.6 PI Controller using Sliding Mode Controller

In case of wind power generation control fuzzy logic (FL) techniques have been suggested [3]. The FL controller has limitations like difficulty in guessing stability and robustness of a control system besides lacking in a formal design approach [3]. A sliding mode (SM) controller is capable of overcoming these drawbacks and has been applied in many fields due to its insensitivity to some external disturbances and variations in system parameters [3]. Rejecting disturbances effectively and obtaining robust parameters are the control objectives of all controllers (PI, Fuzzy-PI, and SM) [3]

The fuzzy controller adjusted the parameters of PI generating new parameters which fit all operating conditions on the basis of error and its derivative. 3 membership functions for the input signal, 4 for proportional gain and 2 for integral gain were used [3]. The machine was tested in ideal conditions and different step inputs were applied to an active and reactive power. The dynamic response for PI, Fuzzy-PI and SM controllers was investigated. The Fuzzy-PI controller gave the best transient result with settling time reduced considerably, faster damping of oscillations and limited peak overshoot.

6. CONCLUSION

Among the various techniques used for controlling the with regards to the transients, the Fuzzy-PI controller gave best settling time and faster damping of oscillations along with limited peak overshoot. In case of sliding mode controller provides great stability and robustness as it is insensitive to external disturbances and variations in system parameters. In all the control techniques PI controllers have been used invariably in which the biggest difficulty faced is the tuning of the controller. However, swarm optimization provides the best optimal parameters for PI controllers and improved the transient response of the system over a wide range of operating oscillations. However, none of the controllers compared so far in this paper have used PID controller. Hence the performance of the various control topologies for the controller in case of DFIG connected to the grid needs to be investigated.

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