Development of Optimal Controllers for a DFIG Based Wind Farm in a Smart Grid Under Variable Wind Speed Conditions

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***Abstract*- Variations in wind speed causes different transient responses in a Doubly Fed Induction Generator (DFIG) based wind farm. Transients during grid disturbances, depending on controller parameters can lead to a system collapse, especially when there are significant fluctuations in wind speed despite the presence of SmartParks (energy storage). When a fault is introduced, the variable frequency converter (VFC) is the most susceptible part in a DFIG. The VFC is controlled by a set of Proportional Integral (PI) controllers. Parameters of PI controllers are very difficult to tune using traditional methods due to nonlinearity in DFIGs and the increasing complexity of a smart grid. This paper presents an implementation of a new efficient heuristic approach – the Mean Variance Optimization (MVO) algorithm, on a digital signal processor, for online tuning of PI controllers on the rotor side converter of a DFIG. With the MVO optimized PI controllers on the wind farm and the entire smart grid remains stable under grid disturbances for a wide range of wind speeds. The results demonstrate that intelligent controller tuning is critical for optimal operation of DFIG based wind farms in a smart grid despite the presence of energy storage.**

***Index Terms*- Doubly fed induction generator, mean variance optimization algorithm, PI controllers, smart grid, SmartParks, wind farms.**

I. INTRODUCTION

The technology of variable-speed wind turbines equipped with Doubly Fed Induction Generator (DFIG) has been subjected to extensive research due to its higher energy yield, reduced power fluctuation, improved VAR supply and cheaper price as compared to other traditional wind turbine technologies [1]. In DFIGs, the induction generator is grid connected at the stator terminals, but the rotor terminals are connected to the grid via a partial-load variable frequency AC/DC/AC converter and a transformer [2]. This increases the efficiency of a DFIG since the Variable Frequency Converter (VFC) requires only a fraction of the total power to achieve full control of the generator.

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Reduction in power fluctuations and improvement in dynamic performance during transient disturbances in DFIGs are achieved through decoupled control of active and reactive power of the generator [3]. These qualities of the DFIG based wind turbines make them a preferred technology when compared to other variable speed wind generators and Permanent Magnet Synchronous Generators (PMSGs) with primary converters. However, the VFC of a DFIG and its power electronics (IGBT-switches) are highly sensitive to transient disturbances in a power network. When subjected to faults or voltage sags, the rotor-side converter of the VFC might be blocked due to protection from overcurrent in the rotor circuit and the wind turbine can be tripped from the system [2]. The VFC is controlled by a set of Proportional Integral (PI) controllers. With optimally designed controllers, the wind generator can withstand transient grid disturbances under a range of different wind speed conditions.

A smart electric power grid consisting of a wind farm and multiple distributed SmartParks (large number of plug-in electric vehicles in a parking lot) was presented in [4]. Further investigation showed that it is necessary to retune the PI controllers as wind speeds were changed and different grid disturbances were experienced despite the presence of energy storage. It was observed that the transient response of the smart grid varied with different wind speeds. In a practical power system, it is desired that a system is capable of withstanding grid faults over a range of varying wind speeds. In order to achieve this goal, it is highly necessary to tune the PI controllers of the rotor side converter of the VFC.

However, it is difficult to optimally tune PI controllers due to the high nonlinearity and complexity of DFIG based wind farm in a smart grid. Various heuristic search methods such as genetic algorithms, tabu search, particle swarm optimization and simulated annealing have been applied to optimize the parameters of PI controllers. These algorithms, although efficient in determining near-optimal parameters, are computationally intensive and require many iterations especially if there is significant fluctuations in the wind speeds.

In this paper, a new population-based stochastic optimization technique called Mean Variance Optimization (MVO) algorithm is implemented on a digital signal processor for online tuning of the PI controllers of the wind generator in a smart grid system, simulated in the Real-Time Digital Simulator (RTDS), operating under variable wind speed conditions and grid disturbances.

II. SMART GRID MODEL

The smart grid test system presented in this study includes a DFIG based wind farm and SmartParks (Fig. 1). The system has two other synchronous generators and an infinite bus, and three interconnected areas. In a typical city, there will be several SmartParks distributed throughout the city in distances of one to few miles. In order to represent this, six three-phase Plug-in Electric Vehicle (PEV) parking lots (PL1 to PL6) are added to Area 2 of this system at bus 13. Bus 13 is an additional bus added to the original 12-bus system [5] in order to connect the PEV SmartParks. Bus 13 is connected to bus 6 through 22 kV/230 kV step-up transformers. The smart grid test system (Fig. 1) is implemented on the RTDS [6].

A 400 MW wind farm is modeled using a single DFIG for this study. It uses back-to-back PWM converters for variable speed wind power generation. The control objective of the grid side converter is to keep the dc link voltage constant regardless of the magnitude and direction of the rotor power [4]. A stator oriented vector control approach is used where the direct axis current is used to control the dc link voltage and the quadrature axis current is used to control the reactive power and in turn the voltage at the point of common coupling. The objective of the Rotor Side Converter (RSC) is to control the active and reactive power from the stator. This is achieved by putting the d-axis of the rotor reference frame along the stator flux vector. The q-axis current reference is generated directly from the commanded electrical power and the d-axis current reference is generated from the stator reactive power command. The electrical power command is generated from the optimum operating point tracking strategy [4], when the wind speed is below a certain value. The pitch control does not work at that time and the wind turbine captures maximum possible power at the available wind speed. But, if the wind speed goes beyond a certain value, the pitch control limits the power generated by the wind turbine. The rotor side and grid side converter control strategy is shown in Fig. 2.

When a fault is introduced at the wind farm bus, the resulting voltage drop leads to an imbalance between the turbine input power and the generator output power causing high current in the stator windings of the DFIG. In DFIGs there is magnetic coupling between the stator and the rotor side of the converter, thus an increase in current in the stator winding leads to an increase in currents in the rotor windings as well. When this rotor current reaches a threshold, the rotor-side converter of the DFIG stops switching and the wind turbine is severed from the system [2]. In Fig. 3, it is noticed that at 11m/s, a six cycle (100 ms) three phase line to ground fault at the wind farm bus led to the tripping of the wind generator. Therefore, it is essential to re-tune the proportional integral controllers that control the rotor side converter of the DFIG for this wind speed. However, with varying wind speeds the transient response of the system changes as observed in Fig. 3. At a wind speed of 13m/s, the system can withstand up to six cycles (100ms) of fault. However, at a wind speed of 11 m/s, there is a system collapse with the same fault. This occurs due to the high overshoot of the rotor current which leads to stator flux oscillations during the transient state after the fault introduction. Thus, the rotor current oscillates with a frequency near the synchronous frequency (Fig. 3). Therefore, it is necessary that the PI controllers are optimally tuned to withstand grid faults at different wind speeds, despite the presence of energy storage in a smart grid environment.

III. DEVELOPMENT OF OPTIMAL PI CONTROLLERS

The converter action determines the operation of a DFIG based wind farm during transient disturbances in a power system [2]. If the PI controllers of the rotor side converter are tuned properly, it is possible to limit the rotor current and therefore improve the performance of the converter during transient disturbances. Since tuning of PI controllers using traditional methods are computationally expensive and exhaustive, and difficult due to the nonlinearities in the system, MVO is used in this paper to find the optimal parameters of the RSC controller online and in a computationally intelligent manner.

MVO algorithm depicted in Fig. 4 is a new population-based stochastic optimization technique introduced in [7]. The mapping function used transforms the uniformly distributed random variation into a population attained so far. The MVO algorithm finds the near optimal solution and is simple to implement. The MVO requires only one fitness evaluation per iteration independent of the number of individuals in the population. In many other heuristic algorithms that exist today, this is not the case. The number of fitness evaluations is proportional to the number of individuals/particles/chromosomes in the population. Fitness evaluation is most time consuming task in tuning using heuristic approaches. Lesser number of fitness evaluations is preferred for fast and online tuning of PI controllers. The MVO algorithm is therefore a very attractive and computational efficient algorithm for online tuning of controllers.

The following steps were followed to implement MVO algorithm for developing optimal PI controllers:

1. Population: A population of two was used similar to the original MVO paper [7].

2. Dimension: Three PI controllers in the rotor side converter are tuned. Each PI controller has a proportional gain and an integral time constant.

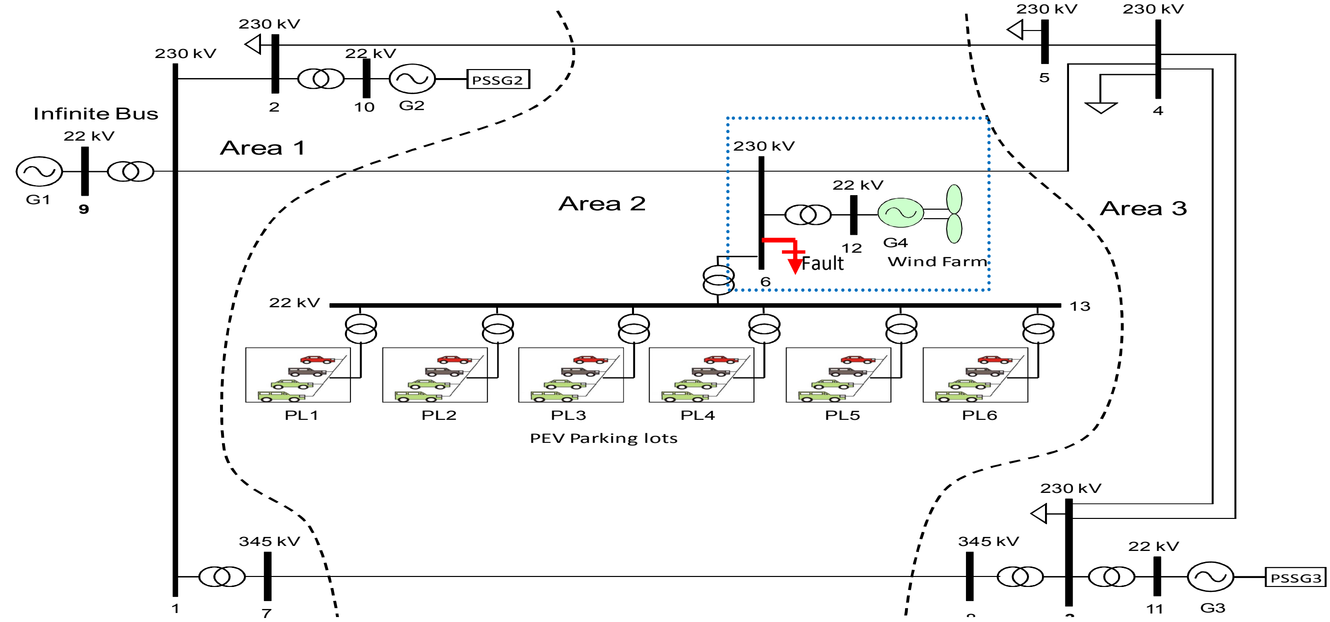

Fig.1. Smart grid with Wind Farm and Smart Parks

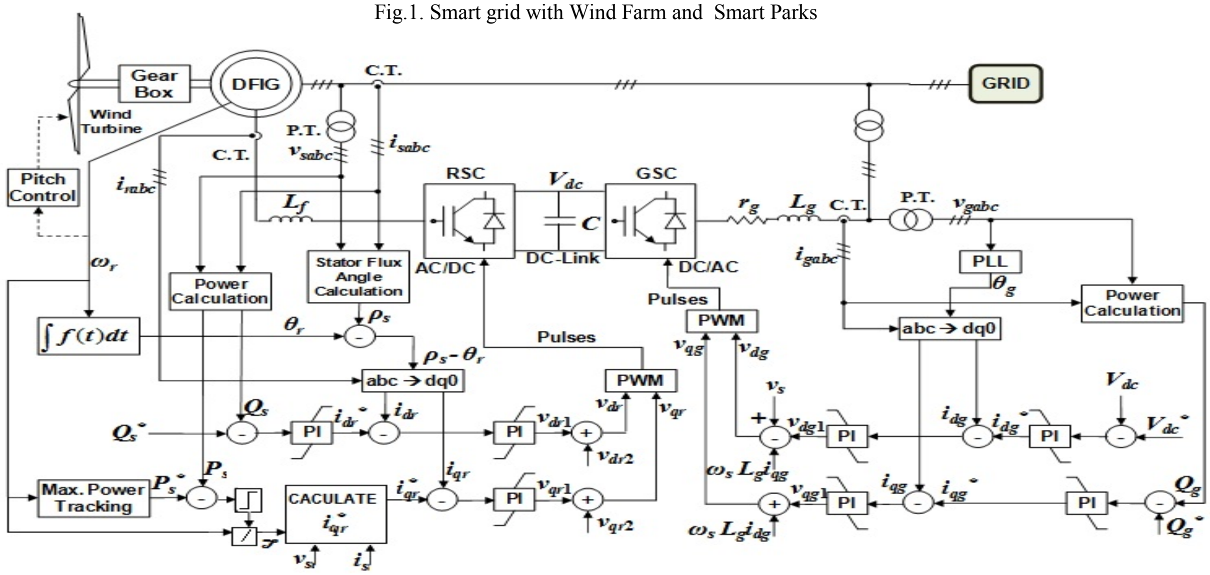

Fig. 2 Rotor and stator side controls of the DFIG based wind farm

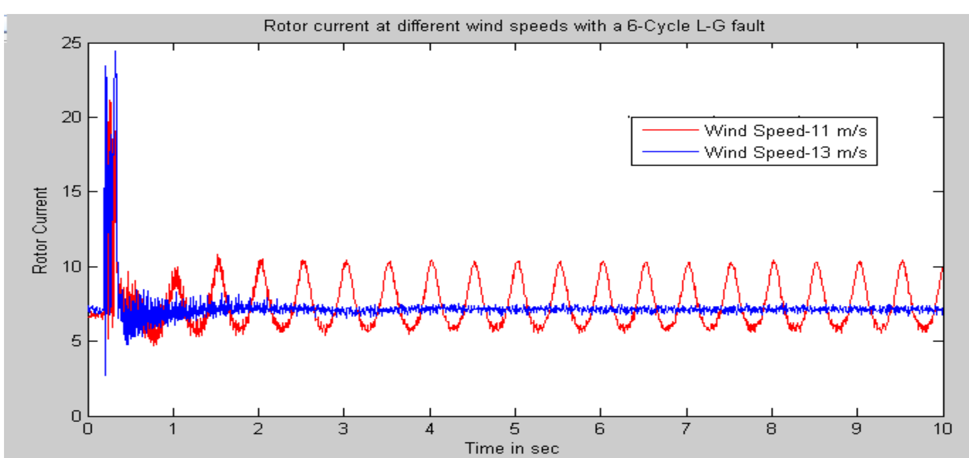

Fig. 3. Comparison of rotor currents at two different wind speeds of 13 m/s and 11 m/s for a three phsae line-ground fault of 6 cycles (100 ms) applied at the wind farm bus.

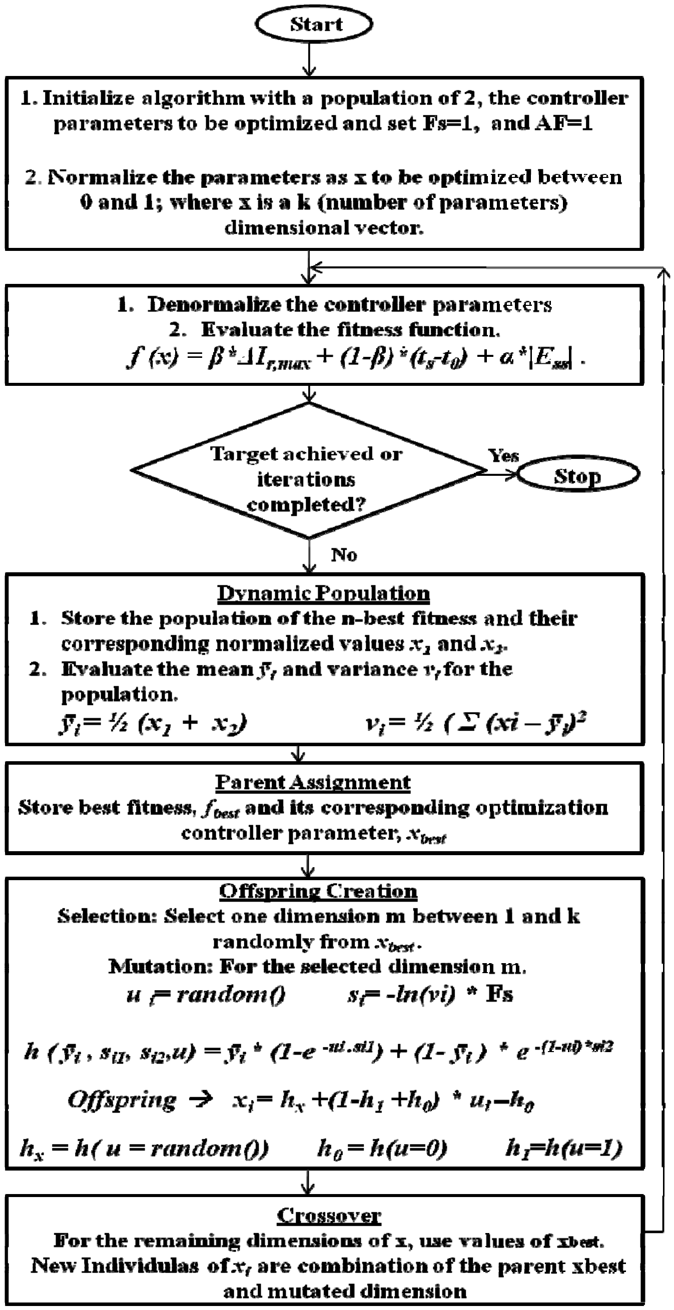

Fig. 4. Mean variance optimization flowchart for PI controller tuning

Thus, there are six parameters to be optimized by the MVO which determined the dimension of the optimization problem to be six i.e. $x = [\, K_w, K_d, K_q, T_w, T_d, T_q \,]$.

3. Fitness Function: The goal of the MVO is to find optimal parameters for the PI controllers by minimizing some fitness function. In this paper, optimization was done in order to reduce the over-shoot current, settling time and the steady state error of the rotor current for three phase to ground faults at the wind farm bus. The following fitness function dependent on wind speed (w_S) is used to evaluate the system transient response:

$$f(w_S) = \beta * \Delta I_{r,max} + (1-\beta) * (t_s - t_0) + \alpha * |E_{ss}| \,. \qquad (1)$$

where $\Delta I_{r,max}$ is the overshoot current; $(t_s - t_0)$ represents the settling time and E_{ss} stands for the steady state error. β and α are the weighting factors that are used to satisfy different design requirements. However, as discussed in Section II, different wind speeds produces different transient response for the wind farm. Hence tuning of the PI controllers is required so that the system is stable not only at one wind speed condition but over a wide range of wind speed conditions. In order to develop PI controllers optimized for a range of wind speeds, fitness was evaluated at three different wind speeds (8m/s, 10m/s and 13 m/s) and a cumulative fitness (F_{total}) was computed:

$$F_{total} = f(8) + f(10) + f(13). \qquad (2)$$

4. Limitations: Proportional gains and integral time constants of PI controllers are selected to be between $0.001 \le K \le 50$ and $0.001\text{sec} \le T \le 2$ sec, respectively.

5. Termination criterion: a maximum of 1000 MVO iterations are allowed.

6. Selection criteria: There are three selection criteria proposed for selection of dimensions to be mutated in [7]. Random selection of one of six dimensions was implemented in this paper. Only one dimension was selected for mutation at a time because optimization was carried out online, and extreme changes in controller behavior could initiate system instability.

7. Mutation and crossover are carried out using the formulas from the flowchart depicted in Fig. 4.

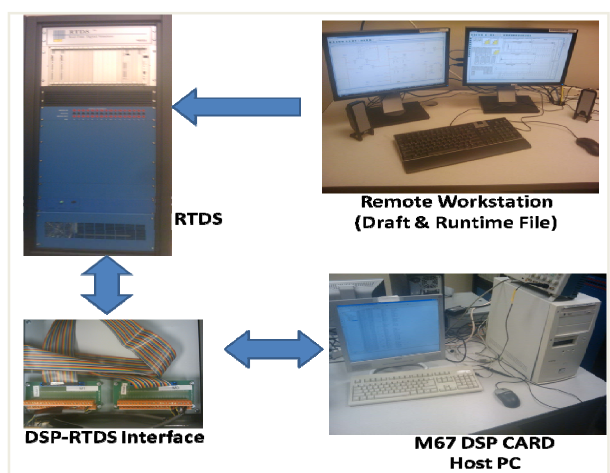

Fig. 5. Laboratory hardware set-up for online tuning including RTDS and DSP

The MVO algorithm is implemented on an Innovative Integration M67 DSP card which is based on the Texas Instruments TMS 3206701 processor. The M67 card operates at 160 MHz and is equipped with two A/D and two D/A conversion modules and is interfaced with the RTDS as shown in Fig. 5. The analog rotor current (I_r) signal sent by the RTDS is converted to a digital signal by the A/D block of the DSP and is used to calculate the fitness function of the MVO algorithm. The MVO outputs are the optimized PI controller parameters and are sent to the RTDS as analog voltage signals in the range of ±10 V. These voltages are converted in the RSCAD software and used as the new proportional gains and the time integral constants of the PI controllers of the RSC.

In order to carry out the online tuning of the PI controllers, a ten cycle (166 ms) three phase line to ground fault is applied at bus 6 (shown in the dashed block in Fig. 1) with the rest of the system represented by an infinite bus. After the optimization was completed, the optimized parameters were introduced in the smart grid system of Fig. 1, and test studies to evaluate the performance of the optimized controllers are carried out as presented in Section IV.

IV. Results

The goal of the MVO algorithm based optimization is to reduce oscillations in the rotor current due to transient disturbances for a range of wind speed conditions. It is noticed that the optimization resulted in a fast fitness reduction in the first 50 iterations following gradual reductions until 655 iterations. The parameters of the PI controllers on the RSC of the DFIG (Fig. 2) were initially tuned manually for a constant wind speed of 8 m/s. These parameters of the RSC controllers are then optimized for varying wind speed conditions using the MVO algorithm. The values of the initial and the optimized parameters are shown in Table I.

TABLE I
INITIAL AND OPTIMAL PI CONTROLLER PARAMETERS

	K_w	K_d	K_q	T_w	T_d	T_q
Initial	0.4000	25.0000	5.0000	0.0350	0.0150	0.0150
Opt-imal	0.9149	7.2186	32.1450	0.3580	1.3569	1.9840

The following case studies are carried out to compare the performance of the optimized controllers to the manual tuned controllers:

Case I: Three-Phase Short Circuit at a Wind Speed of 8 m/s

A ten cycle (166 ms) temporary three-phase short circuit fault is applied at the wind farm bus operating at a wind speed of 8 m/s. Fig. 6 shows the rotor current is limited to 14 kA when using optimized parameters but with manual tuned parameters the rotor current exceeds 19kA. Although the system stabilizes after fault introduction with both optimized and manual tuned parameters, the reduction in the overshoot current led to a better stability in the smart grid system.

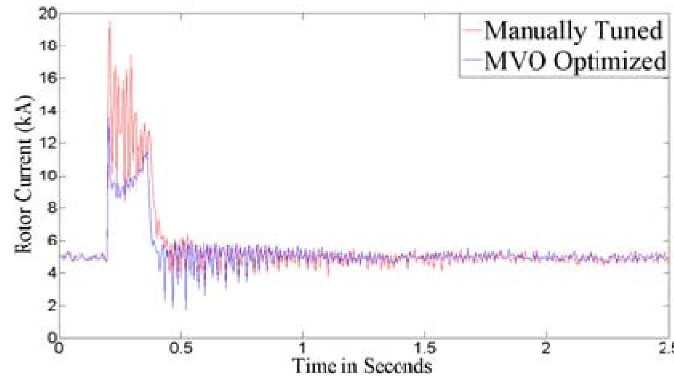

Fig. 6. Comparison of rotor currents (kA) at wind speed of 8 m/s with and without optimization for a 10 cycles (166 ms) three-phase line-ground fault applied at the wind farm bus.

Case II: Three-Phase Short Circuit at a Wind Speed of 11 m/s

The wind speed is now increased to 11 m/s and a similar ten cycle (166 ms) short circuit is applied at the wind farm bus. Fig. 7 shows the rotor current is limited to 24 kA when using optimized parameters in comparison to 31 kA with manual tuned parameters. This reduction of the over current prevents the blocking of the rotor side of the variable frequency converter of the DFIG and thus leads to a continuous operation of the DFIG. Thus, the system stabilizes after the fault with the optimized RSC controllers. However, with the manually tuned controllers, the high overshoot of the rotor current leads to stator flux oscillations during the transient state after the fault and the rotor current oscillates with a frequency near the synchronous frequency.

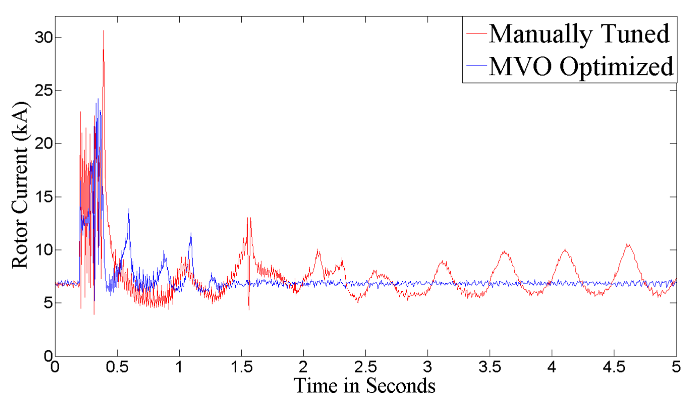

Fig. 7. Comparison of rotor currents (kA) at wind speed of 11 m/s (with and without optimization for a 10 cycles (166 ms) three-phase line-ground applied at the wind farm bus.

Case III: Three-Phase Short Circuit at a Wind Speed of 13 m/s

Another comparison is made between the optimized and the manually tuned controllers for operation at a wind speed of 13 m/s. Fig. 8 shows similar results as in Case II. Optimized controllers are able to withstand the ten cycle fault whereas manually tuned controllers fail to provide continuous operation after the fault. Thus, it can be concluded that the optimal controllers designed for a range of wind speeds are able to withstand a fault better than manually tuned controllers at a single speed. After analysis of the PI controller signals, saturation of the PI controllers was not observed for such responses. Hence, an anti-windup mechanism was not necessary in the design of the PI controllers.

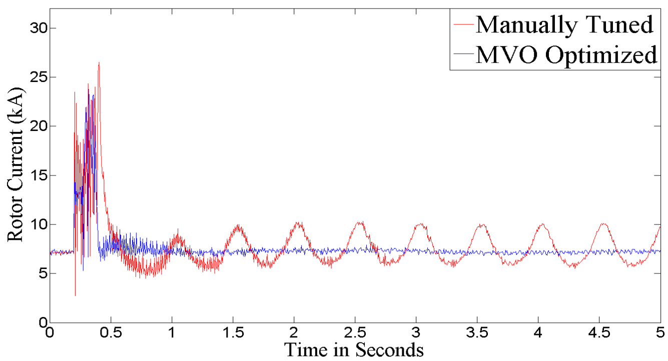

Fig. 8. Comparison of rotor currents (kA) at wind speed of 13 m/s (left) with and without optimization after a 10 cycles (166 ms) three-phase line-ground fault is applied at the wind farm bus.

Case IV: Effect of Controller Optimization on the Rest of the Generators of the Smart Grid System

When a three-phase 10 cycle (166 ms) line to ground for a wind speed of 13 m/s is applied at the wind farm bus, the optimized controllers not only improves the stability of the wind farm but also improve the stability of the other two generators G2 and G3 (Fig. 2) in the smart grid. Figs. 9 and 10 show the machine speeds of these generators with optimized and manually tuned controllers on the DFIG. With optimized controllers, the speed deviations of the two generators settle down after the fault is removed, and the generators remain synchronized to the grid. However, with manually tuned controllers the speeds of the two generators oscillate after the fault introduction. Thus, with manually tuned design, the two generators G2 and G3 are tripped from the system after fault

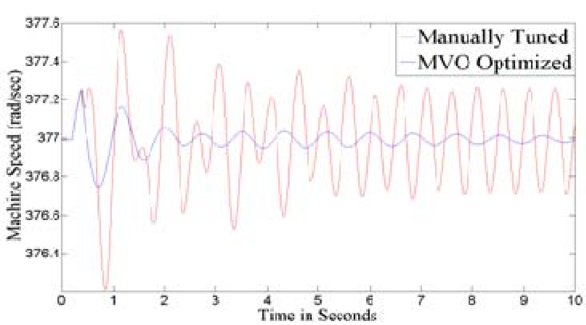

Fig. 9. Comparison of machine speeds (rad/sec) of Generator 2 in the smart grid at wind speed of 13 m/s with and without optimization for a 10 cycle (166 ms) three-phase line-ground fault.

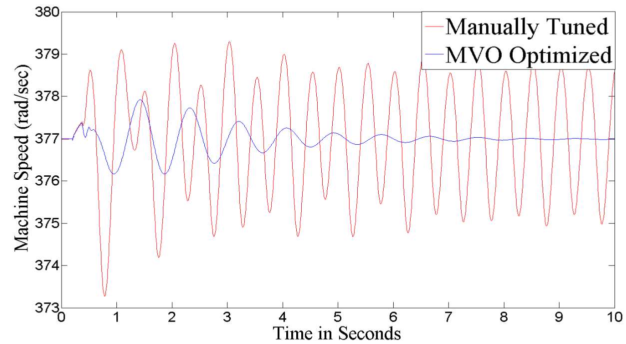

Fig. 10. Comparison of machine speeds (rad/sec) of Generator 3 in the smart grid at wind speed of 13 m/s with and without optimization for a 10 cycle (166 ms) three-phase line-ground fault.

V. Conclusion

This paper has presented that transients during grid disturbances, depending on controller parameters can lead to a system collapse, especially when there are significant fluctuations in wind speed despite the presence of SmartParks (energy storage). The high nonlinearity and computational inefficiency of traditional controller tuning methods demands an intelligent and efficient technique to develop optimal controllers for a DFIG based wind farm. Hence, a novel heuristic MVO algorithm is implemented on a digital signal processor for online optimization of the PI controller parameters on the rotor side converter of a DFIG based wind farm. The MVO improves the stability of the system under grid disturbances for a range of wind speed conditions. As a result of the optimally tuned controllers, transient performance of the other generators in the smart grid is improved as well. Future studies may involve extending this approach from online to a real time tuning controller approach.

Referees

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