Enhancement in PI Parameter Prediction Using Segmented Mutation based Genetic Algorithm

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Abstract

This paper present the improvement in integration of electrical grid and induction generator with self-excited mode. This induction generators are mostly used in wind turbine. For this purpose static synchronous compensator is adapted with direct adaptive strategy with some adjustable controller parameters and an adjusting mechanism to adjust them using model reference adaptive control (MRAC). Model reference adaptive control is used to balance reactive power flow of this integration. Voltage-source inverter sinusoidal pulse width modulation handles the different operational condition in wind energy system. According to that ability of staying connected with grid in Brownout and blackout also increases. Because of occurrence of some faults at coupling of grid and generator, some abnormal operational condition generates. In proposed model, Genetic Algorithm with modified mutation function is used to tune proportional-integral controller. Instead of conventional random selection function for mutation, a modified algorithm is applied. For evaluation purpose Zafarana wind system integrated with Egyptian 220 networks is used. Results shows an improvement in performance of proposed model reference adaptive control using genetic algorithm which balances the current, voltage and speed of wind generator. It is also observed ability of staying connected with system under abnormal situation and during Brownout and blackout also increases with segmented mutation based genetic algorithm.

Keywords

Enhancement in Wind Energy Systems, PI Controller, Segmented Mutation based Genetic Algorithm, Power Generation, Renewable Resources.

Introduction

Renewable energy is the latest trend in power generation, renewable resources is used for it, which are naturally replenished on a human timescale. Wind energy is growing on very high scale, its demand is increasing every year, which is why power transmission capability and reliability of wind resources is important to maintain [1]. Because of this increased application of wind resources, researches towards enhancing the security, stability and control of wind power management in necessary. Integrating wind generation system with power control, design, optimisation can enhance this system. Although there are some limitations and constraints with this integration of power system with wind power generation. Low voltage ride through (LVRT) is one of the restriction among several. Reactive power regulation (VAR) is important to maintain the flow between this power and wind system which extensively takes care of voltage drops at common coupling point (PCC). Many researches are going on the field of Low voltage ride through [2] [3]. Wind system uses various types of generator. Previously wind system used to run on SEIG (self-excited induction), permanent magnet synchronous, switched reluctance and DFIG (double-fed induction) generator. Currently wound rotor (DFIG) and squirrel cage generators are mostly used. SEIG has an advantage like speed over wide area, generator without brush along with it has active and reactive both power control mechanisms, hence it is widely used in wind system [4].

For self-excited induction generator, to regulate the VAR component, VAR compensator is present in turbine generator. Wind system with SEIG generators shows in-efficient performance as it is not fault tolerant. Problem with this integration is it releases reactive power in faulty conditions. Because of this VAR implementation in SEIG is required so that Low voltage ride through improves [5]. Voltage level at the integration of system to VAR is directly affected by Reactive power. It can be controlled by regulating the phase angle of voltage of system and injected voltage. Flexible AC transmission system are mostly used for VAR control. Along with VAR control, there are different application of transmission system in power system control and operations. There are different types of system which provides flexible AC transmission. Voltage source inverters based transmission system is mostly used in STATCOM (static synchronous compensator). STATCOM provides enhancement in performance of system as well as it improves the integration of power system with wind system. These characteristic is important in fault tolerance of this integration with self-excited induction generators [6]. Static synchronous compensator also helps for easy integration of wind energy conversion system into electric grid [7]. This integration is consist of wind system, generators, power system and static synchronous compensator, which makes it more complex. Different control mechanism were proposed for this concern. PI controller is still used in many wind energy conversion systems [8][12]. Problem with this mechanism is, it needs high accuracy of models which is used for wind-power system generators and static synchronous compensator.

To balance this, number of turbines in wind energy conversion system need to be increase. Which leads to better management of regulation of all parameters which used in integration. In many researches PI controller's parameter are regulated by approximate linearization techniques. DFIG control parameters are optimised by PSO (Particle swarm optimisation). Genetic algorithm has proven optimisation in many fields. It has also provided enhancement in power system Application [11][12]. Particle swarm optimisation and Genetic algorithm is used for regulating PID (PI derivative) parameters online [13][14]. Even though the performance of all this mechanism is good for PI derivative parameters, but it need be regulated offline for some operating conditions. This indicates that this mechanisms are prefect for per-specified operating condition. But this is not always the case, if there is any modification in pre-specified operating condition, then performance may get reduced. Few Adaptive control mechanism were suggested which control the offline regulation of variable operating condition.

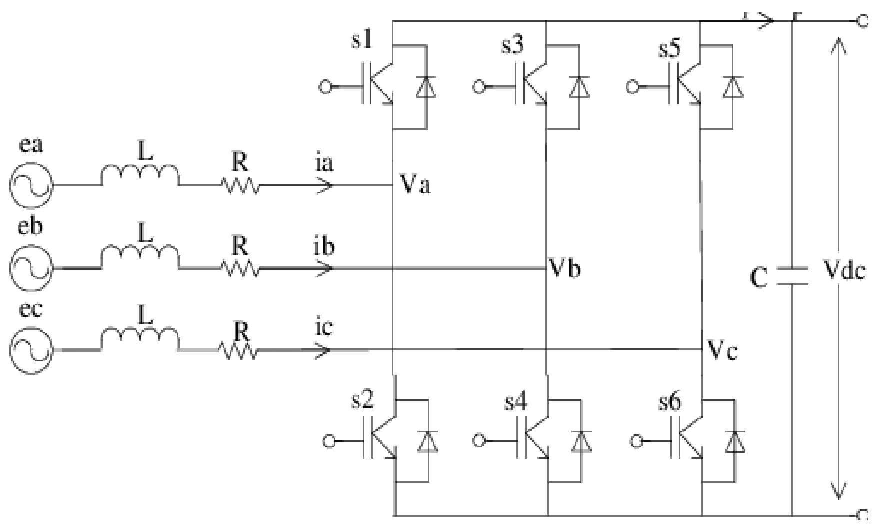

Figure 1 Circuit diagram of static synchronous compensator

Mosaad and Salem in their research LFC based adaptive PID controller using ANN and ANFIS techniques describes application of neuro fuzzy systems and artificial neural network in Adaptive PID controller [18]. In their later research they provided case study based comparison of model predictive and adaptive PID control [19]. In many researches the application of Adaptive dynamic programming techniques has proven an enhanced results for problems of power system [15]. MRAC (Model reference adaptive control) technique is also evolved which is being used in many power system [16][17]. Model reference adaptive control applies closed range parameter which are dependent on variable operating condition. The adaption is based on difference present between output of system and proposed reference model.

It's a complex problem to integrate static synchronous compensator with wind energy conversion system to improve Low voltage ride through. Changing operation condition and non-linarites increases the complexity. Along with that there are more system in this problem, and different mechanism is proposed to control it [18][19].Even though these mechanism handles the Low voltage ride through using static synchronous compensator, but the problem with non-linarites is not considered, and the variable parameters based on different operating conditions is not optimised.

This research works towards Model reference adaptive control of static synchronous compensator which enhances the performance of integration of wind energy conversion system with power grid. This controller helps to control reactive power flow between static synchronous compensator and WECS. This increases the low voltage ride through, enhances the voltage regulation at PCC and maintain grid faults and generator acceleration. To regulate the reactive power flow between the system and static synchronous compensator, this model uses SPWM (sinusoidal pulse width modulation) which generates switching pulse to control voltage angle. This eventually handles voltage support at PCC. It control adaptive variable flow, whereas PI controller handles static gain. In the performance analysis proposed mechanism is compared with PI controller with Genetic algorithm. For testing purpose unified Egyptian 220 kV with integration of Zafarana wind system is used.

System and Compensator

Proposed system is mainly composed of 3 parts which are generators, wind turbine and static synchronous compensator. Wind turbines modelling performs power extraction and maintain the speed of wind [20]. self-excited induction type generator configured with fix speed is used. MATLAB Simulink is used to model the system. Figure 1 shows, static synchronous compensator circuit is composed of two converters and it's equivalent circuit. 3 phase voltage at source is Va1, Vb1 and Vc1 while at static synchronous compensator inverter it is Vas, Vbs, Vcs. Converter 1 is a rectifier which is uncontrollable as power flow from AC to DC. However for converter 2, power flows in reverse way. Capacitor changes its model to discharging from charging, this is based on converter 2 state. When converter 2 is in ON state, then capacitor start charging till max value of voltage from first converter.

Converter 2 remains at this voltage level because of not having power flow. Turning ON converter 2, leads the AC voltage output of static synchronous compensator. Which transfer the power from DC to AC side. Because of this voltage of DC capacitor decreases, while static synchronous compensator consumes the VAR. This mode is termed as lagging phase. However in leading phase, voltage of static synchronous compensator lags voltage at supply, which eventually increases the voltage at DC capacitor and generates VAR at static synchronous compensator. Phase angle between this two regulates the VAR flow between system and static synchronous compensator.

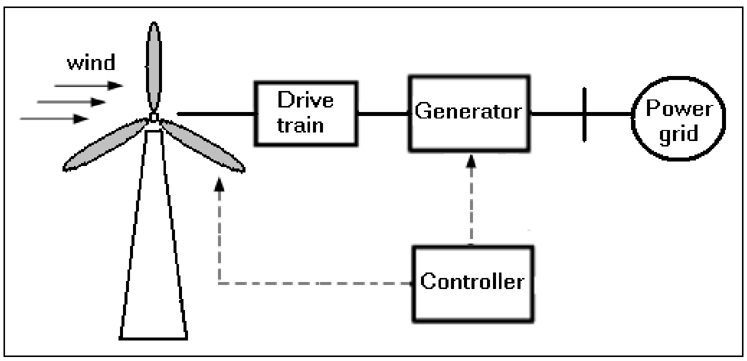

Figure 2 Wind energy system

For testing system, Zafarana wind system integrated with Egyptian network is used. Same has been illustrated in Figure 2. In Egypt, Zafarana is most productive wind system. Average speed of wind is 9.4 m/s in this area. Wind energy conversion system is consist of 3 feeders, each one has 4 turbine. The self-excited induction type generator used in this system consumes 690 V and 660 KW. Step up type of transformer is used to connect Egyptian network with wind system. Zafarana to PCC with 220kV network distance is 6.5km. As illustrated in Grid is consist of 6 node and 2 generators [22][23].Source of the VAR is capacitor with 250kVAR. This is also called as excitation capacitor as it is used for exciting squirrel cage induction, because this 3 generator are self-excited induction type. This is because rotor do not have sufficient residual flux for exciting the machine which leads to failure of self-excited induction type generator [23]. Wind turbine has rotor diameter of 47 meter and wind speed is 9.4 m/s. Generator has rated power of 660 KW, stator frequency of 0.0092, stator inductance is 0.1686 H, rotor resistance is 0.0121, rotor inductance is 0.1446, mutual inductance is 5.6863. Static synchronous compensator has STATCOM rating 4 MVA, series line resistance of 0.1301 Ω, series line reactance is2.42 Ω, DC link capacitance is 750 F.

Proposed Genetic Algorithm based System

Reactive Power Control

Voltage at PCC can be control by regulation of reactive power by static synchronous compensator and wind system. PI controller with regulated parameter along with genetic algorithm is used to minimise the ISE (Integral square error) between voltage at PCC and reference voltage. It contains current at PCC and d-q frame transformation of 3 phase voltage. Proposed 2 PI controller is used to control static synchronous compensator. First controller is use to update reference quadrature axis. Current – Iq ref this is based on difference between reference voltage and vector of measure. Second controller is use to handle α angle, which is summed with phase angle at PCC ϴ. Pulse width modulation (SPWM) technique is used to create switching pulse of 3 levels inverter of static synchronous compensator to maintain the inverter voltage released by system which is based on α angle. α angle is consider as fluctuating control signal.

Genetic Algorithm for Tuning PI Control Parameters

Genetic algorithm is use to find the most optimised solution. It is evolved by Charles Darwin. This works on the principle of natural selection. In this individual are treated as a population which used to find out the genes and chromosomes to get offspring of the next generation.

It involves 5 phases:

1. Initial population
   This process involves the initialization all population. In which variable is mentioned as genes and its set is chromosomes. This set is known as Initial population.
2. Fitness function
   Fitness score determines the individual score to fit the current state. Based on this score it is selection for production
3. Selection
   Fitness function is used to select the individual to pass the gene to the next generation. Fitness score plays an important role in selection phase In this phase two parents for production are selected.
4. Crossover
   It is an most important phase in Genetic algorithm. In crossover phase, two individual meets to create a new one which can be more optimistic solution. This is based on cross

over point. Selection of cross over point is based on random function. This selects the random point for crossover and offspring are created.

5. Mutation

In this phase a modification is performed on the newly formed offspring. Low random changes are performed on the offspring which may include flipping of some bits as shown in figure 3.

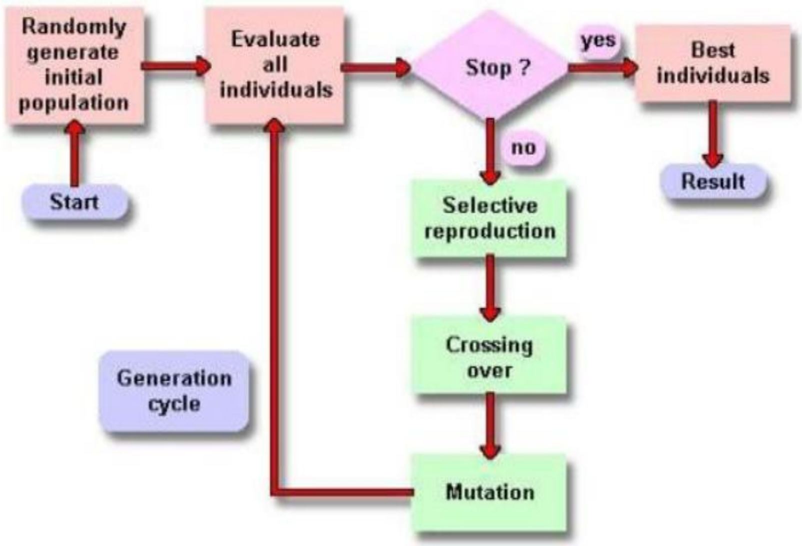

Figure 3 Conventional Genetic Algorithm

This is performed in python using numpy, pandas and sklearn libraries.

Modified Genetics Algorithm

This algorithm enhances the mutation steps. Conventional mutation step deals with single parent which is fittest among the two. Also bit selection procedure is carried out using Random function. As discussed bit is reversed in the step from 0 to 1 and 1 to 0 irrespective for minimization or maximization problem. In Conventional genetic algorithm difference from parents and offspring is only of 1 bit. But there is a major drawback of the system, this bit can be a MSB which can leads to major changes in the offspring. However if the bit is LSB it will not change the offspring which is again a conflict for finding the optimised solution. Therefore bit which is present somewhere between middle is selected for mutation. This considered as a optimised offspring for next generation. However it is difficult to find the best possible middle bit from the parent. Proposed advancement in mutation used to find the best possible bit for mutation.

Step 1 : Fittest parent is selected and identification of type of problem either minimization or maximization.

Step 2 : In case of maximization problem 0 is converted to 1 and for minimization problem 1 is converted to 0.

Step 3 : Parent is divided into several segment with 3 or 4 bits in each one.

Step 4 : If the count of segment is odd then middle bit is selected. For even count of segment, any one from both middle segment is selected.

Step 5 : In this step, bit is selected based on type of problem which was selected in step 1.

Step 6 : If the problem is maximization, then bit with value 0 is selected. If there are multiple 0 bits then the one which is close to MSB side is selected for swapping. If the whole segment does not have 0 bit then the segment on the left side is selected.

Step 7 : If the problem is minimization, then bit with value 1 is selected. If there are multiple 1 bits then the one which is close to MSB side is selected for swapping. If the whole segment does not have 1 bit then the segment on the right side is selected.

Modified Genetic Algorithm is used to calculate the optimised PI control parameter for regulating flow of reactive power between static synchronous compensator based grid and wind system. In this mechanism there are 2 PI controller for compensator, first and second controller both has 2 parameters Kp and Ki. In any given disturbance the optimum 4 values of 2 controller is computed with minimum cost J function.

Minimum Cost J function is calculated by (1):

$$J = \int_0^t (\mathrm{ev}(t)^2)\mathrm{d}t \quad (1)$$

Where ev is error difference from voltage at PCC and reference voltage. This J function is Voltage at PCC which directly affected by VAR flow. α and Flow of VAR between grid and wind system is regulated by output signal of this controllers. Hence this J function is depend on parameter of PI controller.

All probability output for Kp and Ki has to be code into binary in chromosomes. ISE fitness function helps to detect the most optimum value [4][13]. PI regulation algorithm, describes the flowchart of genetic algorithm for regulating the Kp and Ki parameter [4].

Model Reference Adaptive Control

All control parameters which is computed from genetics algorithm is calculated at range of operating conditions, this is also termed as static control parameter. In this case if there is any changes in the operating condition of system, then parameter should be adjusted in such a way that it will maintain an optimum value of objective function. This require one more optimization step, and this can be executed offline. This is an adaptive control mechanism. Model reference adaptive control based MIT tool is applied in this research to increase performance of PCC voltage profile through VAR based static synchronous compensator. To handle the system response, Model reference adaptive control mechanism creates a close loop controller updated with newly computed parameter. In this mechanism, reference model provides expected response (V_{model}). This will be the response of the system, during disturbance. System output Vout is calculated and compared with response output with updated control parameter. This is explained in Figure 4(a). In this way adaptive controllers uses voltage obtained by reference model, instead of constant reference voltage unlike static controller. Using this reference model and output voltage is tracked with only reference voltage then control parameter is adjusted to minimise the cost function. Control signal and α is used to maintain the Pulse width modulation. MIT is discover to design and enhance aircraft and autopilot. In this research, MIT rules were applied to develop model reference adaptive control.

This Functionality is used to update the value of objective function, which apparently update cost function. But in static controller, objective function is based on difference of voltage at PCC and reference voltage. In MIT, *e* is difference between voltage at reference model and output voltage, which helps to maintain α.

$$E(t) = Vout - Vmodel \quad (2)$$

Where $V_{(out)}$ is voltage at output, while $V_{(PCC)}$ is PCC Voltage.

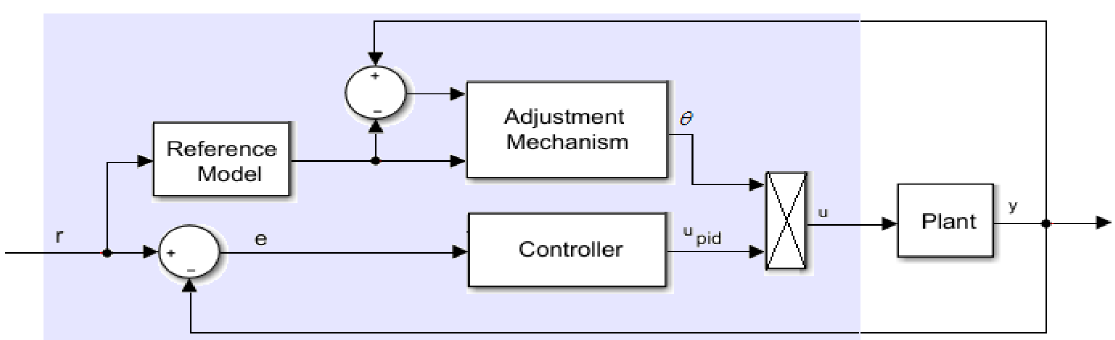

Figure 4(a) Block diagramof Model reference adapted controller

While updated objective function is calculated as

$$J_{\mathrm{MIT}}(\alpha) = \frac{1}{2} e(t)^2 \quad (3)$$

Adjustment of α is carried out to make the value of $J_{(MIT)}$ function 0, as a result change rate of objective function moves in negative gradient direction, which is

$$\frac{d\alpha}{dt} = -\gamma \frac{\partial J_{MIT}}{\partial \alpha} \quad (4)$$

$$\frac{d\alpha}{dt} = -\gamma e \frac{\partial e}{\partial \alpha} \quad (5)$$

Positive value of γ maintain the controller's adaptive gain. Figure 4(b) illustrate the block diagram of MRAC of static synchronous compensator for integration of wind system into the grid. As described in 2,3,4 and 5 equation, both controller updates adaptively using MIT rule.

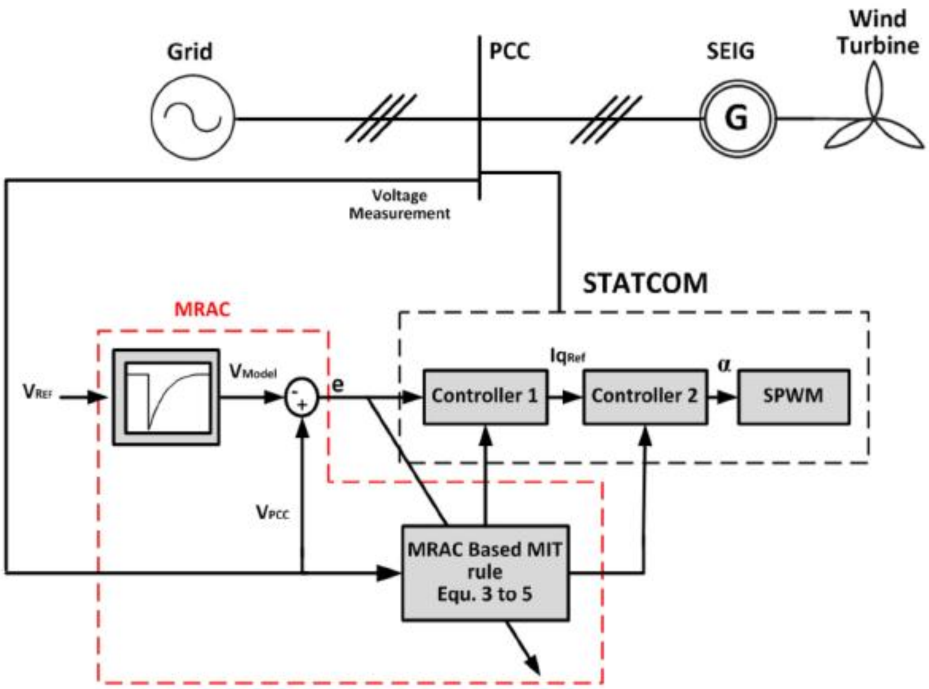

Figure 4(b) Block diagramof Model reference adapted controller integrated to grid

This update is depended on the difference between voltage at reference model and voltage at PCC. If there is any change in Voltage at PCC because of fault, then this controller maintain the voltage at reference model.

Integration of Static Synchronous Compensator into Wind System through LVRT

Integration of static synchronous compensator into the wind energy conversion system is a complicated process also it involves lot of restrictions from operators which involves wind parks, control of VAR factor and low voltage ride through capability of generators to handle the voltage dips. Grid code maintain this in graphical form with time vs voltage chart. This code also put some restriction on tripping of the system after and during the disturbance. This code is mainly consist of 2 zones, higher voltage zone is low voltage ride through and lower voltage zone is trip zone. Static synchronous compensator rating for wind system integration into electric grid is based on different parameter. In previous research many equations were proposed for computation of Static synchronous compensator rating calculation [23][26].

In this research VAR component needed for compensation is considered to be 100% of wind energy system rating. Fault is apply at PCC, and that point's voltage is measured[26]. By reduction in VAR value near minimum, complies PCC voltage at grid code. Figure 2 illustrates the wind energy system which is used for testing purpose. It is integrated with proposed adaptive control of static synchronous compensator for enhancing the integration of controller with genetic algorithm to optimise low voltage ride through.

STATCOM Rating

Rating of static synchronous compensator is based on different parameter. As described in figure 3, VAR value is adjusted based on voltage at PCC.

Initially the minimum VAR is injected which is equal to wind energy system i.e. 7. MW, and then gradually the value of minimum VAR is reduced in such a way that magnitude of PCC voltage remains in the range of operating region. In figure 5(a), the value of minimum VAR which can injected during fault in continuous operating condition is 4 MVA. Hence 4 MVA static synchronous compensator is used in this analysis. Rating of static synchronous compensator used in this research is approximately 50% of total wind energy system rating.

PI Regulated by Genetic Algorithm Control

Pseudo code for Genetic algorithm
START
Generate the initial population
Compute fitness
REPEAT
Selection
Crossover
Mutation with proposed approach
Compute fitness

UNTIL population has converged
STOP

To comply with Nordel grid code Genetic algorithm is applied to two controller which helps to manage static synchronous compensator integrated with wind system. For testing purpose 2 fault cleaning conditions at PCC is considered. This conditions illustrate the static synchronous compensator for regulation of voltage and different integration effect of wind rotor speed. Service disconnection during voltage drop at integration and Low voltage ride through is also studied in this integration.

Algorithm for PI Regulation

Step 1: Start
Step 2: Initialization of all population which consist of all genes and chromosomes for regulation
Step 3: computation of fitness function
Step 4: if power generation is less than max generation then stop generation
Step 5: if power generation is greater than max generation start reproduction
Step 6: perform crossover and mutation with specified bits and minimization problem
Step 7: Increase generation value by 1
Step 8: Iterate the procedure from step 3 until power generation is less than max generation

Experimental Analysis

This section describes the experimental analysis result. In test case 1, cleaning fault time is set from 3 to 3.25 seconds, with fault as 0.25 at PCC. This system is compared without integration of static synchronous compensator and with integrated code, it is observed that the performance of system get extensively affected by major instability and short circuit in PCC voltage. Same system then tested with the integration of static synchronous compensator, it is observed that performance of voltage profile is improved. It shows that static synchronous compensator integration retain the generators connection. Without integration of static synchronous compensator, generator speed increases to higher undesired but acceptable levels. With integration, VAR value is regulated which maintains the speed of generator's rotor. Without integration, the speed was increased by 17%, even though it is an acceptable level, it creates unnecessary effects on system. But with integration rotor speed is increased by 11%, this increases the performance of wind energy system. Waveform of current flow I_{pcc} with and without static synchronous compensator. Integration maintains the VAR value at PCC, which reduces the current flow in fault operating conditions. In the frame of fault time of 0.25 seconds, integrated static synchronous compensator is studied. Voltage and rotor speed is recoded at steady condition, even the generators remains connected to the system, in faulty condition. This integration also maintains the fault current. Two PI controller and Advanced genetic algorithm based control parameter is studied. With Integration, performance of voltage profile improves and remains in LVTR levels.

In test case 2, fault time is considered to be 0.35 seconds. PI control parameter remains the same. PI Advanced Genetic algorithm controlled parameter is considered same as first case with 0.25 seconds clearing time, Two control parameter for controller 1 is 0.958 and 0.532, while for controller 2 this control parameters are 0.835 and 0.368, This is illustrated in figure 5(a). In this case PI controller parameters are static because of this generators gets disconnected with and without integration of static synchronous compensator. It the system is configured with the two controller parameter, then generator remains connected as voltage profile matches with code. Without integration the speed of rotor is more accelerated, while in case of integration speed is maintained.

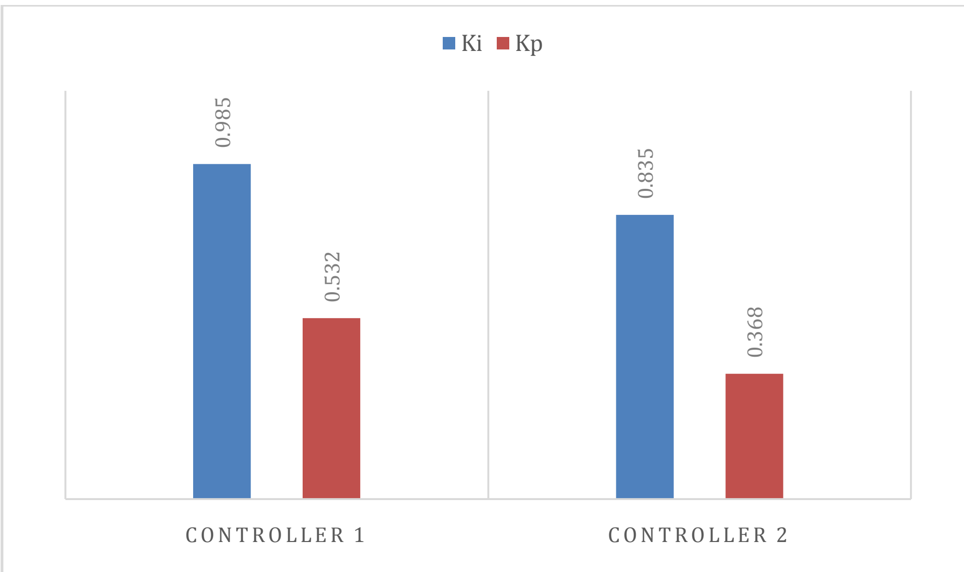

Figure 5 (a) Test case 1

In regards with rotor speed, adaptive Advanced genetic algorithm based PI controller performance is better than static PI controllers. Two PI control parameter for controller 1 is 0.752 and 0.631, while for controller 2 this control parameters are 0.835 and 0.368. This is illustrated in figure 5(b). Two PI control parameter for advanced Genetic algorithm is for controller 1 is 0.73 and 0.421, while for controller 2 this control parameters are 0.612 and 0.211, This is illustrated in figure 5(c).

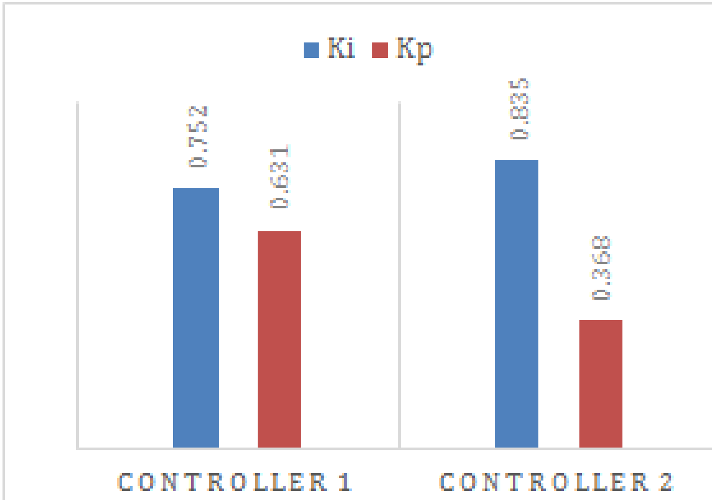

Figure 5(b) Genetic algorithm based controller

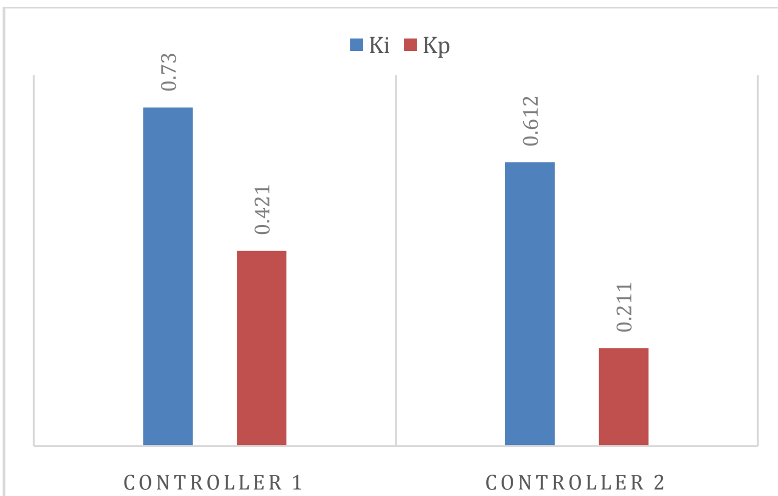

Figure 5(c) With segmented mutation based GA
Figure 5 PI controller parameter

But the fault clearing time for second case is more than first case and generators remains connected to the system. In this way adaptive controllers increases the effectiveness of generators along with this it provides a back up to the system in case of circuit breaks.

From these description, the performance of the systems enhances with the integration of static synchronous compensator and proposed genetic algorithm based tuned control parameter, which keeps updating on updated operating condition, that is adaptive control mechanism. Adaptive tuning is somehow difficult and impossible to implement as it needs to perform offline and the time required for optimisation is more. Model reference adaptive control based tuning is used to perform this task online.

Model Reference Adaptive Control

In this performance test, Model reference adaptive control mechanism is introduced into the system. Selection of model reference is an important step in implementing this mechanism. Model reference maintains the tuning of controller parameters. As shown in block diagram, V_{model} with exponential increases from 0.5 *p.u.* to 1 *p.u.* in 0.25 seconds fault test. Voltage reference of system is set to 1 *p.u.* reference and model reference voltage. Based on *α*, VAR flow between wind energy system and static synchronous compensator is regulated for tracking the voltage at reference model. Even though adaptive control mechanism cannot regulate the voltage at reference model, the performance of the system improves further with modified genetic algorithm based integration when compare to static control parameter, as shown in figure 6(a). Minimum voltage and maximum overshoot in this model is 0.49 and 10% respectively while for PI genetic algorithm it is 0.30 and 16%. Time complexity of proposed model references is also better. This factors enhances the performance of proposed system. This proposed system maintains the rate of injection of VAR from static synchronous compensator to PCC and wind energy system. PI based proposed genetic algorithm maintains the VAR values according to the PI parameter computed from proposed genetic algorithm by reducing ISE between reference voltage which is 1 p.u. and PCC.figure6(b) illustrates voltage regulation of LVTR, MARC, conventional genetic algorithm.

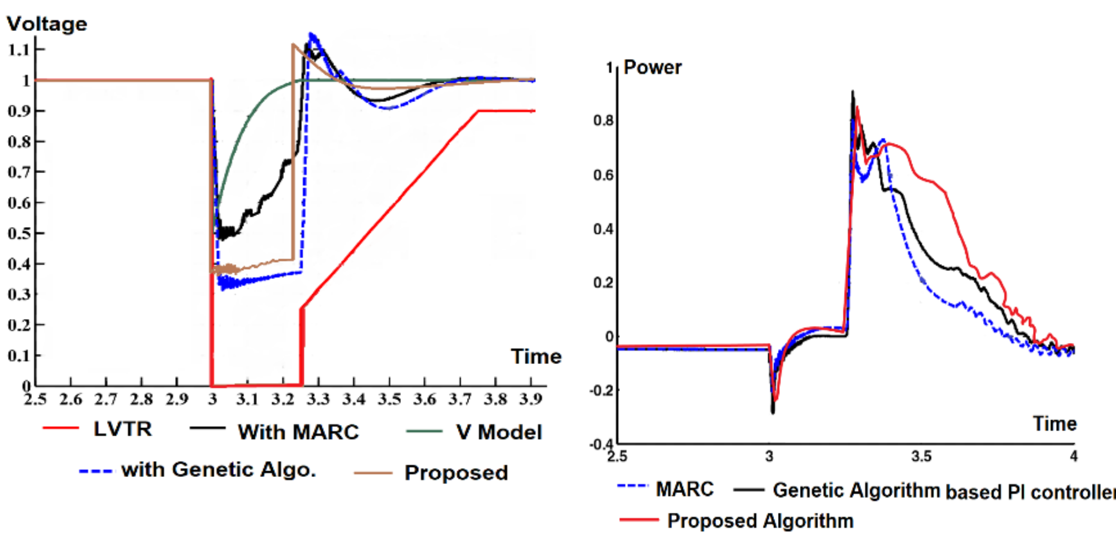

Figure 6a) Comaprison of voltage at PCCFigure 6b) PI- GA and MRAC reactive power comparison

Figure 6 Performance Analysis - Model reference adaptive control

In the second phase of texting 0.35 seconds of fault clearing time is considered. In this test voltage at PCC with integration of static PI component, with adaptive component and with Model reference adaptive control. Voltage used at this test. It is observed that with propose schema, voltage profile shows significant enhancement in performance as compare to other. Along with this generator perform its application without disconnection. For testing purpose another 0.5 seconds of fault clearing time is added, and generator operation is observed. It is observed that generator perform continuously without any disconnections from system. Also it is complies with the code.

Waveform of current with clearing time of 0.25 seconds, 0.35 seconds and 0.5 seconds. Even though the clearing time is increased, the proposed system reduces the level of fault current. This case scenario with increased clearing time and reduce fault current without increasing rating of static synchronous compensator describes the enhancement in the proposed integrated system. From this statics, it is evaluated that proposed integration enhances the low voltage ride through and voltage profile of wind energy system. Minimum voltage is regulated to 0.5 p.u. from proposed system, whereas previous research manage to regulated it by 0.2 and 0.25 [23]. To reach the steady condition of 1 p.u., time required for proposed controller is 0.37 seconds for conventional GA while it is reduced further to 0.33 seconds for modified genetic algorithm, while it was previously0.45 seconds and 0.4 seconds.

Conclusions

This research represent the integration of static synchronous compensator into wind energy system to improve the performance of the system with consideration of low voltage ride through. Proposed system regulates the VAR flow from static synchronous compensator to system grid by chaining the SPWM angle. This also enhances the voltage profile of the system. In this research voltage profile, current flow for PI controller regulated by genetic algorithm and proposed mechanism is compared. segmented Mutation improves the accuracy of STATCOM based PI controller further. Proposed integration shows better performance in regards with speed of generator and voltage of system as compare to adaptive and static PI controllers. In Experimental analysis section of this system, proposed controller improves the low voltage ride through ability of the system, thereby it improves the working of wind energy conversion system in abnormal and faulty condition. Generator remains connected to the system even for long fault clear time. This shows the overall improved performance of the wind energy system for voltage profile, current flow, low voltage ride through and disconnection issues in fault clearing time.

References

Tang, Y., He, H., & Wen, J. (2015). Power system stability control for a wind farm based on adaptive dynamic programming. *IEEE Transactions on Smart Grid*, *6*(1), 166–177.

Espinoza, N., Bongiorno, M., & Carlson, O. (2015). Novel LVRT testing method for wind turbines using flexible VSC technology. *IEEE Transactions on Sustain. Energy*, *6*(3), 1140–1149.

Ruan, J.Y., Lu, Z.X., Qiao, Y., & Min, Y. (2016). Analysis on applicability problems of the aggregation-based representation of wind farms considering DFIGs' LVRT behaviors. *IEEE Transactions on Power Systems*, *31*(6), 4953-4965.

Mosaad, M.I., Elkalashy, N.I., & Ashmawy, M.G. (2018). Integrating adaptive control of renewable distributed switched reluctance generation and feeder protection coordination. *Electric Power Systems Research*, *154*, 452-462.

El-Moursi, M.S. (2011). Fault ride through capability enhancement for self-excited induction generator-based wind parks by installing fault current limiters. *IET renewable power generation*, *5*(4), 269-280.

Wessels, C., Hoffmann, N., Molinas, M., & Fuchs, F.W. (2012). StatCom control at wind farms with fixed-speed induction generators under asymmetrical grid faults. *IEEE Transactions on Industrial Electronics*, *60*(7), 2864-2873.

Mohod, S.W., & Aware, M.V. (2010). A STATCOM-control scheme for grid connected wind energy system for power quality improvement. *IEEE Systems Journal*, *4*(3), 346-352.

Hazrati, A., & Jalilian, A. (2012). Grid side harmonic current mitigation in DFIG based wind plants. *In IEEE Proceedings of 17th Conference on Electrical Power Distribution*, 1-7.

Zhang, Y., Cheng, M., & Chen, Z. (2014). Load mitigation of unbalanced wind turbines using PI-R individual pitch control. *IET Renewable Power Generation*, *9*(3), 262-271.

Freijedo, F.D., Vidal, A., Yepes, A.G., Guerrero, J.M., Lopez, O., Malvar, J., & Doval-Gandoy, J. (2015).Tuning of synchronous-frame PI current controllers in grid-connected converters operating at a low sampling rate by MIMO root locus. *IEEE Transactions on Industrial Electronics*, *62*(8), 5006-5017.

Mossad, M.I., Azab, M., & Abu-Siada, A. (2014). Transformer parameters estimation from nameplate data using evolutionary programming techniques. *IEEE transactions on power delivery*, *29*(5), 2118-2123.

Mossad, M.I., Azab, M., & Abu-Siada, A. (2016). A novel evolutionary technique to estimate induction machine parameters from name plate data. *In IEEE XXII International Conference on Electrical Machines (ICEM)*, 66-71.

Mosaad, M.I., & Salem, F. (2014). LFC based adaptive PID controller using ANN and ANFIS techniques. *Journal of Electrical Systems and Information Technology*, *1*(3), 212-222.

Salem, F., & Mosaad, M.I. (2015). A comparison between MPC and optimal PID controllers: case studies. *IET Conference on Michael Faraday IET International Summit: MFIIS-2015, Kolkata, India*, 59–65.

Werbos, P.J. (2011). Computational intelligence for the smart grid-history, challenges, and opportunities. *IEEE Computational Intelligence Magazine*, *6*(3), 14–21.

Venayagamoorthy, G.K. (2011). Dynamic, stochastic, computational, and scalable technologies for smart grids. *IEEE Computational Intelligence Magazine*, *6*(3), 22–35.

Kumar, R., Das, S., & Chattopadhyay, A.K. (2016). Comparative assessment of two different model reference adaptive system schemes for speed-sensorless control of induction motor drives. *IET Electric Power Applications*, *10*(2), 141–154.

Khanna, R., Zhang, Q., Stanchina, W.E., Reed, G.F., & Mao, Z.H. (2013). Maximum power point tracking using model reference adaptive control. *IEEE Transactions on power Electronics*, *29*(3), 1490-1499.

Suul, J.A., Molinas, M., & Undeland, T. (2010). STATCOM-based indirect torque control of induction machines during voltage recovery after grid faults. *IEEE Transactions on power Electronics*, *25*(5), 1240–1250.

El-Moursi, M.S., Bak-Jensen, B., & Abdel-Rahman, M.H. (2010). Novel STATCOM controller for mitigating SSR and damping power system oscillations in a series compensated wind park. *IEEE Transactions on power Electronics*, *25*(2), 429–441.

Molina, D., Venayagamoorthy, G.K., Liang, J., & Harley, R.G. (2013). Intelligent local area signals based damping of power system oscillations using virtual generators and approximate dynamic programming. *IEEE Transactions on Smart Grid*, *4*(1), 498-508.

Vestas Wind Systems: 'V47–660 kW with OptiTip® and OptiSlip'. http://www.vestas.com

Youssef, E.B. (2011). *Performance optimization of wind generators connected to the grid.* Master thesis, Helwan University, Egypt.

Mahfouz, M.M.A., & El Sayed, M.A.H. (2014). Static synchronous compensator sizing for enhancement of fault ride-through capability and voltage stabilization of fixed speed wind farm.*IET Renew. Power Energy*, (8), 1–9.

Swarnkar, P., Jain, S.K., & Nema, R.K. (2010). Effect of adaptation gain on system performance for model reference adaptive control scheme using MIT rule. *Int. Conf. of World Academy of Science, Engineering and Technology, Paris*, 70–75.

Gounder, Y.K., Nanjundappan, D., & Boominathan, V. (2016). Enhancement of transient stability of distribution system with SCIG and DFIG based wind farms using STATCOM. *IET Renewable Power Generation*, *10*(8), 1171–1180.

Noureldeen, O. (2011). Low voltage ride through strategies for SCIG wind turbines interconnected grid. *International Journal of Electrical and Computer Sciences IJECS-IJENS*, *11*(2), 53–55.