Genetic Algorithm-Based Optimization of Overcurrent Relay Coordination for Improved Protection of DFIG Operated Wind Farms

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***Abstract*—Rigorous protection of wind power plants is a critical aspect of the electrical power protection engineering. A proper protection scheme must be planned thoroughly while designing the wind plants to provide safeguarding for the power components in case of fault occurrence. One of the conventional protection apparatus is overcurrent relay (OCR), which is responsible for protecting power systems from impending faults. However, the operation time of OCRs is relatively long and accurate coordination between these relays is convoluted. Moreover, when a fault occurs in wind farm-based power system, several OCRs operate instead of a designated relay to that particular fault location, which could result in unnecessary power loss and disconnection of healthy feeders out of the plant. Therefore, this article proposes a novel genetic algorithm (GA)-based optimization technique for proper coordination of the OCRs in order to provide improved protection of the wind farms. The GA optimization technique has several advantages over other intelligent algorithms, such as high accuracy, fast response, and most importantly, it is capable of achieving optimal solutions considering nonlinear characteristics of OCRs. In this article, the improvement in protection of wind farm is achieved through optimizing the relay settings, reducing their operation time, time setting multiplier of each relay, improving the coordination between relays after implementation of IEC 60255-151:2009 standard. The developed algorithm is tested in simulation for a wind farm model under various fault conditions at random buses and the results are compared with the conventional nonlinear optimization method. It is found that the new approach achieves significant improvement in the operation of OCRs for the wind farm and drastically reduces the accumulative operation time of the relays.**

***Index Terms*—Genetic algorithm (GA), optimization of relay coordination, overcurrent relay (OCR), power system protection, wind farm.**

Manuscript received July 9, 2018; revised January 6, 2019; accepted August 11, 2019. Date of publication September 2, 2019; date of current version October 18, 2019. 2018-PSPC-0634.R1, presented at the 2018 IEEE Industry Applications Society Annual Meeting, Portland, OR, USA, Sep. 23–27, 2018, and approved for publication in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS by the Power Systems Protection Committee of the IEEE Industry Applications Society. This work was supported by the Natural Science and Engineering Research Council (NSERC), Canada under the Discovery Grants-Individual Program. *(Corresponding author: Mohammad Nasir Uddin.)*

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Digital Object Identifier 10.1109/TIA.2019.2939244

I. INTRODUCTION

DUE TO the rapid growth in power demands, the ever-increasing rate of air pollution, and the decrease of nonrenewable fossil fuels, there is an imminent necessity to transfer, at least partially, the dependence on fossil fuels to renewable energy resources. Among these resources, wind power has come to be the mainstream of the renewable energy systems in several countries and is regarded as a reliable and financially reasonable source of electricity [1]. Wind power plants have been vastly employed as the means of power generation in the smart grids as a distribution generation systems [2]. The contribution of wind energy to power generation is holding a considerable share worldwide [3]. The impressive growth in the utilization of wind energy has consequently spawned active research activities in a wide variety of technical fields. Progressively amplification of grids by wind farms has led to the emergence of some significant electrical issues including security, protection, stability, reliability, and power quality. Among these issues, protection aspect plays an enormous role that has drawn the attention of researchers. Although protection of wind farms is very critical and intricate, wind power plants still implement simple protection schemes that lead to different levels of damages to power components in the plant under faulty conditions. Moreover, most of the research works conducted on wind farm protection have been dominantly restricted to the literature and methodologies [4]. In [5], Ndreko *et al.* reported different levels of damage, but the drawbacks of the associated protection systems have been skipped. Although there are partial analyses of centralized protection [6], an overall protection scheme has yet to come to solve the protection crisis in wind plants.

Overcurrent prevention is one of the most crucial areas of protection in wind power systems. The OCRs are mostly used as primary and backup protection in many regions of power networks and power plants. To provide comprehensive protection, the relays must be adequately coordinated with each other, not only to prevent damage to power devices due to current faults, but also to limit the disconnected district to the faulty feeders and improve power quality [7]. Proper power system protective relaying for DFIG-based wind farms and relay coordination is immensely challenging, which have not been addressed adequately in the literature to the best of the authors' knowledge. The conventional protective relay settings provided for the wind farms are not the best possible settings available, and there are scopes of improvement regarding relay operation time and relay coordination. This topic requires solicitous attention and negligence in proper protection would result in reduced power quality, compromise the reliability and stability, and severe health injuries. [8] Besides, optimal coordination of overcurrent relays is hugely demanding and considered as a highly constrained nonlinear programming problem specifically in complex power systems, such as DFIG-based wind farms. Conventional techniques may not be able to solve convoluted grid-fault issues [9]. Unsophisticated techniques, such as linear programming (dual simplex and two-phase simplex) method and nonlinear programming have been implemented to address the solution of the optimal coordination for distribution power system protection. These methods have several drawbacks, such as trapping into local minimum and difficulty to reach at optimal global value [10], [11]. Thus, the methods are proven to be less effective than modern artificial intelligence (AI) techniques, such as genetic Algorithm (GA) optimization technique. The GA can address the nonlinear characteristic of overcurrent relays and optimize the operation time of relays. Moreover, if GA is appropriately developed, the most optimal solution is achieved. Furthermore, the GA-based intelligent protection system is capable to provide significant improvement in relay operation and coordination for the DFIG-based wind farms and thereby ensures enhanced reliability and security for wind farm operation systems.

Despite the massive success of the GA in the protection of power system components, it has never been extensively used to improve the wind farm protection, which leaves a considerable gap in electrical power protection study. Hence, a GA-based optimization algorithm with the formulation of a proper objective function and suitable parameter constraints has been proposed in this article. The relay settings have been optimized by minimizing time setting multiplier (TSM) concerning IEC standards to procure the best possible operating time and coordination for all the overcurrent relays. To verify the efficacy of the developed technique, it has been tested under various fault condition at different positions of the power network. Furthermore, a comparison between the conventional nonlinear optimization method and the developed method was presented to prove the effectiveness and robustness of the proposed approach.

The increasing integration of wind power plants to power grids and their vast utilization have led to the emergence of some electrical issues related to security, protection, stability, reliability, and power quality. Power-line faults and protection failures may cause severe damage to the power systems and accordingly hike the maintenance costs [12]. The major associated problems for protection of wind farms are as follows.

1) Improper and nonoptimal conventional settings for the overcurrent relays in wind farms. If the coordination settings between these relays are not optimal, it will result in miscoordination in high current faults, severe damages to power apparatus, and accidental activation of multiple relays, causing extended power loss, compromised power quality, and stability.
2) The OCR operation times are relatively long during fault incidence. Delayed operation of the relays may result in severe damage to power apparatus, installation and subsequently, endanger personal safety.

These problems result from the lack of optimization in the OCR settings. The following objectives will be the focus of this article to address the solution of the aforementioned problems.

1) Improvement of the protection of wind farms by enhancing the coordination between relays, by optimizing the relay settings according to IEC 60255-151:2009 standard through the optimization of TSM, and subsequently the operation time of each relay.
2) Implementation of the GA, as a powerful optimization branch of artificial intelligence approach, to obtain improved values for each relay settings based on their coordination criteria. Each relay operation time and TSM are optimized by using the GA method, which would consequently contribute to the enhanced protection for wind farms.

Section II of this article, discusses about OCRs, their function, and how they are set and coordinated to provide proper protection. Moreover, IEC standards for setting the OCRs have also been presented. The proposed GA method for the wind farm protection has been discussed in Section III. In Section IV, the wind plant model for protection study has been illustrated and current flow during normal operation and during fault occurrence has been simulated as well. Section V has been dedicated to OCRs settings for the wind plant based on the results obtained in Sections III and IV. Also a comparison between GA and the conventional method results has been illustrated. At the end, the results and findings have been discussed in the conclusion in Section VI.

II. Overcurrent Relay

The OCRs have the same basic I/O signal operation as other types of relays. In these relays, if the incoming current is higher than the preset current value, the relay will send out an output signal to the circuit breaker (CB) to disconnect the circuit in order to protect the power components from the result of excess current. There are three main types of OCRs used in power systems, which are: definite current relay, definite time relay, and inverse time relay. The most common type is inverse time relay, which has an inverse characteristic curve that means the relay operates faster as the current increases. These types of relays operate instantaneously when the current reaches a high limit magnitude, thus, eliminating the damage to the power components [13].

Inverse time OCRs based on their sensitivity to the current and time can have several characteristics, which are reliant on the applications. These OCR types, according to IEC 60255-151:2009 standard is depicted in Table I.

TABLE I
TYPES OF OVERCURRENT RELAYS ACCORDING TO IEC 60255-151:2009

Type of Overcurrent Relay	Operation Time
Normally-Inversed	$T = \frac{0.14 * \text{TSM}}{(I/Ipickup)^{0.02} - 1}$
Very Inversed	$T = \frac{13.5 * \text{TSM}}{(I/Ipickup)^{1} - 1}$
Extremely Inversed	$T = \frac{80 * \text{TSM}}{(I/Ipickup)^{2} - 1}$
Long time-Inversed	$T = \frac{120 * \text{TSM}}{(I/Ipickup)^{1} - 1}$

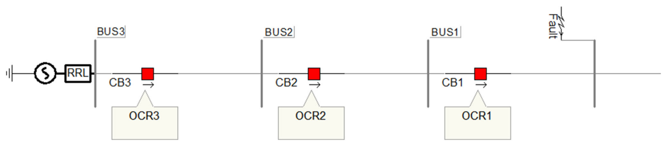

Fig. 1. Overcurrent relay coordination concept.

In this article, in order to attain the best and actual results, the entire overcurrent relays have been successfully modeled by MATLAB software. All the relays have been modeled based on IEC 60255-151:2009 standard where the normally inverse characteristic have been opted in order to provide rational output signal for the circuit breakers in case of any fault in the plant.

In power systems, all these OCRs must be properly coordinated with each other in order to protect the power elements from the fault current. To do so, the vital settings of OCRs, such as plug setting multiplier (PSM) and TSM, which must be properly selected. PSM is varied in the range of 50%–200% and in steps of 25%. This setting is only used for inverse current relays taht detect phase to phase fault. For the relays that detect phase to ground fault, the PSM is quite different. It is varied in the range of 10%–40% in steps of 10%, or in the range of 20%–80% in steps of 20%. The point that should be taken into consideration is that the more PSM the relay has the higher current that the relay requires to trip. The TSM ranges from 0 to 1 in steps of 0.1. However, sometimes it varies in steps of 0.05. The maximum TSM is 1 and the minimum is 0.05. In order to coordinate OCRs with each other, there is a time interval between a primary relay and a backup relay operation and this is called the coordination time interval (CTI). This time interval is in the range of 0.3 and 0.5 s for conventional relays, whereas for the numerical relays it is set at 0.2 s, which means they operate faster compared to the conventional relays [14]. So, in order to coordinate relays with each other, the relay operation time and CTI must be taken into consideration. After the characteristics of these relays are designated, then the coordination of OCRs can be properly undertaken.

Coordination of the OCRs means that the closest relay to the fault location, which is referred to as the primary relay, must trip before the CB, and in case the relay does not trip or malfunctions, the other relay closest to the primary relay, which is called the backup relay, must trip. This coordination is extremely crucial and is conducted in order to decrease the expanded power loss and avert power quality compromise. The coordination phenomenon is depicted in Fig. 1. In this figure, OCR1 as primary protection must trip to the fault. In case of any malfunction, OCR2 as backup protection should trip. Also, if OCR2 does not operate, OCR3 as the second backup protection must trip and disconnect the feeder.

III. PROPOSED GA TECHNIQUE FOR WIND FARM PROTECTION

GA is an advanced and practical method that can be used for a variety of applications to optimize the solutions including problems where the objective functions (OF) are discontinuous stochastic, and nondifferentiable or nonlinear [15]. GA can also be implemented for problems of mixed integer programming where some elements are constrained to be integer valued.

GA fulfills three types of rules at each step to produce the next generation from the in-progress population, which are called selection, crossover, and mutation. In selection, individuals are selected, which are named as parents, to contribute to the population at the next generation. Crossover is then used to combine two parents to create children for the next generation. At the end mutation is implemented in order to apply random changes to individual parents to generate children. The steps are explained in the following sections and the flowchart for the GA approach has also been depicted in Fig. 2.

A. Initialization

At the very beginning stage of the GA, a preliminary pool of random chromosomes referred to "parents" is generated. Parents are essentially sets of random relay settings that must satisfy the defined constraints. Each set of the relay setting is packed into a chromosome hence each chromosome contains TSM for all the relays in the wind farm. The number of TSM sets are referred as population size that must be set properly during initialization. The higher population size selected, the more TSM sets are generated, as a result better settings for relay may be achieved at the end of the GA process, however, if an enormous population size is opted, a much longer time should be provided for the GA to process all the parents based on the selected constraints and may not be suitable for some online applications that high operation speed is required. Thus, a sensible population size based on the optimization problem should be designated. The constraints defined for chromosomes are fundamentally the constraints that are defined for the protective relays. In this article, the constraints for overcurrent relay coordination has been defined as

$$\Delta t_{mb} = t_b - t_m - \text{CTI} \geq 0 \tag{1}$$

$$0.05 \leq \text{TSM} \leq 1 \tag{2}$$

$$\text{TSM}_{i\min} \leq \text{TSM}_i \leq \text{TSM}_{i\max}. \tag{3}$$

In these equations, Δt_{mb} represents discrimination time between the backup and main overcurrent relay, t_b and t_m are the operation time for backup and main relay, respectively, and CTI is the coordination time interval between the main and backup relay. In this article, CTI has been selected as 0.2 s, which is a standard setting for the numerical overcurrent relay. Furthermore, the range of TSM has also been defined, which varies from 0.05 to 1 according to the standards. It is obvious

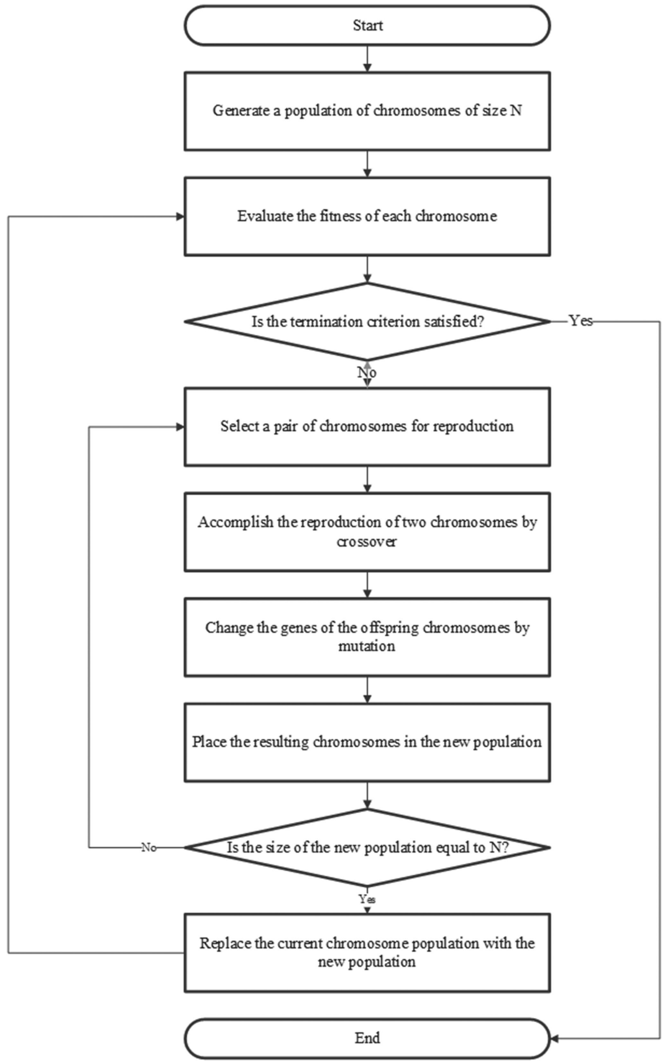

Fig. 2. Flowchart for genetic algorithm approach.

that the TSM cannot afford to be 0 as the relay will operate instantaneously and causes miscoordination. Finally, the relation between TSM of each relay with other relays have also been formulated as a constraint in order to avert any malfunction and miscoordination between the relays.

B. Evaluation

The fitness of each chromosome is evaluated by fitness function or objective function, so that only the most suitable chromosomes, in other words, the best relay settings are selected and processed to the next step. Since the purpose of this article is to minimize the operation time of relays and TSM of each relay to improve the performance of overcurrent relays in wind farms, it is sensible to formulate our objective, as shown in the following equation:

$$\mathrm{OF} = \min \sum_{i=1}^{n} (t_i)^2 \tag{4}$$

where t_i is the operation time of overcurrent relays. By applying this OF, we are able to minimize the operation time of relays and accordingly obtain the TSM values, however, the coordination constraints are ignored, which may cause miscoordination for relays in wind farm, specifically for symmetrical fault type. Hence, it is immensely vital to introduce coordination constraints to our OF as

$$\mathrm{OF} = \min \left[\sum_{i=1}^{n} (t_i)^2 + \sum_{m\&b=1}^{n} (\Delta t_{mb})^2 \right]. \tag{5}$$

In this equation, Δt_{mb} denotes discrimination time between the backup and main overcurrent relay. In this protection study, another expression, $\beta[\Delta t_{mb} - |\Delta t_{mb}|]$ has been added in order to enhance the coordination between relays and optimize the relay settings. So the entire coordination constraint is $[\Delta t_{mb} - \beta(\Delta t_{mb} - |\Delta t_{mb}|)]$. For the given equation, we can consider the following two states:

$$\begin{aligned} &[\Delta t_{\ mb} - \ \beta \left(\Delta t_{mb} - \ |\Delta t_{\ mb}| \right)] \\ &= \begin{cases} \Delta t_{\ mb}, & \Delta t_{\ mb} > 0 \\ (1 + 2\beta) \left(\Delta t_{\ mb} \right), & \Delta t_{\ mb} < 0 \end{cases}. \end{aligned} \tag{6}$$

These constraints defined for OF would help the GA selection process to grant more opportunity to the chromosomes containing TSM to survive and reproduce superior TSM values, as explained in Section C in the following. So, by considering relay operation time, coordination constraints for main and backup relay and added expression for coordination improvement, the specific OF developed to optimize the relay settings has been defined as in the equation

$$\mathrm{OF} = \alpha_1 \sum_{i=1}^{n} (t_i)^2 + \alpha_2 \sum_{m\&b=1}^{n} \left(\Delta t_{mb} - \beta \left(\Delta t_{mb} - |\Delta t_{mb}| \right) \right)^2. \tag{7}$$

$$t_i = \frac{0.14 * \mathrm{TSM}_i}{(I/\mathrm{Ipickup})^{0.02} - 1}. \tag{8}$$

The first term in the OF is the sum of the OCRs operation time, second term is the coordination constraint, and α_1, α_2, and β are the weighting factors, which are devised to empower and increase the concentration of each section. t_i represents the operating time of OCRs, which is derived from (8) based on IEC 60255-151:2009 and is accordingly replaced in (7) to calculate TSM and obtain optimal values for the TSM. Finally, Δt_{mb} is the discrimination time between the main and backup protective relays.

The weighting factors α_1, α_2, and β can be customized depending on the optimization application. In every application these parameters may be changed to obtain the best results and optimize the relay performance. In this article, after testing several values during GA-based simulation in MATLAB by trial and error method, the suitable parameters are selected as: $\alpha_1 = 1$, $\alpha_2 = 2$, $\beta = 100$, so that the OF achieves the minimum TSM values for each overcurrent relay and consequently, optimize the operation time of the relays based on IEC standards and the coordination constraints defined in GA.

C. Selection

Based on the values obtained by OF for each generation in the previous step that represents "parents," some "parents" are more divergent that others. With this regard, according to a concept known as elitism, those "parents" who have more optimal OF values in the "parents" chromosome pool, should be granted more opportunities to survive, hence they are enabled to spawn further offsprings. Afterward, roulette wheel as a selection method is used, so that the minimum values for the OF are picked and processed to the next step. In other words, at this stage, the minimum TSM values are selected and processed to the next step.

D. Crossover and Mutation

At this stage, "parents" will be responsible for reproduction of offsprings through genetic operation crossover and mutation process. Crossover operation is applied to combine the genetic information of 2 "parents" to reproduce a new offspring, which represents a new TSM for an overcurrent relay. Mutation operator is responsible for imposing new genetic information and variation to the heterogeneous population with the purpose of improving genes that would contribute to obtaining better TSM for relays. It should be mentioned that the mutation may have counterproductive effect on genes in a way that during mutation process, a bad gene may be introduced and consequently an inferior TSM is produced. Thus, during setting GA parameters, a reasonable mutation value should be selected and a large value should be refrained. After the crossover and mutation for all the chromosomes is carried out, the entire generated offspring will be examined by constraint criteria and those who failed will be eliminated. The new offsprings are the new improved TSMs, which will be qualified to go through the next step. This process is repeated until the size of the new population is equal to the size of the preceding population.

E. Selection of Next Generation From Children and Parents

At this step, all the "parents" and offsprings (TSMs) that have satisfied the constraints and fitness criteria examined through OF, will replace the previous generation. The entire GA process is repeated until the termination criteria is satisfied as illustrated in the flowchart shown in Fig. 2.

F. Termination

The GA process is terminated by the termination settings defined for GA. For this article, the termination criteria has been chosen as "reaching highest ranking solution fitness" and "successive iterations no longer produce better results" (optimal convergence), which means OF has reached its optimal rate and cannot be minimized any further, subsequently, the most minimum TSM values for the relays have been attained.

IV. Wind Farm Modeling for Protection in MATLAB

There are several types of feeder topologies currently applied in the wind farms. Radial, bifurcated radial, feeder-subfeeder, and looped topologies are the most common types employed, each yielding their own distinct advantages and disadvantages [16]. These factors and other criteria, such as the implemented wind turbine technology with respect to the coverters and generators, mode of operation either grid-connected or islanded (where the wind farm operate autonomously), wind profiles, available tower placement, and costs must be considered in order when determining which topology to be employed. However, the most common wind farm topology that has been used extensively in many countries is feeder-subfeeder topology due to its protection criteria advantage compared to other types of wind farms topologies. Feeder-subfeeder topologies are typically employed where clusters of towers are distributed over large areas. They are typically comprised of a single cable feeding remotely located switchgear with several subfeeder. The significant protection advantage of this type of wind farm topology is that during a fault incidence at any feeder only the faulty feeder will be disconnected from the intertie system and the rest of the other feeders and wind turbines will remain connected. However, in other types of wind farm topologies, such as loop or radial, any fault on the feeder, may result in disconection of the entire wind turbines from the power grid, which is a drastically catastrophic situation that would compromise power quality, reliability, and integrity of the wind farm as a reliable source of DG. The typical wind farm modeled and simulated by the MATLAB/Simulink as one of the most common type of wind farm topology available in many regions is shown in Fig. 3. This type of wind farm is based on a schematic proposed by Schweitzer Engineering Laboratories known as SEL for power system protection study [17].

The wind power plant modeled in this article, consists of 5 DFIG-based wind turbines where each of them produce 2 MW. Their voltage and frequency are 575 V and 60 Hz, respectively. Transformers corresponding to each wind turbine has voltage ratio of 575 V/25 KV in star-delta configuration where the star side is earthed. The last transformer on the intertie line corresponding to the grid side has the voltage ratio of 25 KV/110 KV and delta star configuration where star is earthed. The transmission lines have 10 km length each. Moreover, a grounding transformer has also been installed next to the intertie line in order to manage the unbalanced load on the power system as well as to handle high magnitude of excessive current during single line to ground fault. The breakers have been highlighted as orange color named by CB1, CB2, …, CB12 and the corresponding relays to each breakers, are highlighted as red color shown by R1, R2, …, R12.

In wind power plants, since the wind speed is not always stable and is fluctuating all the time, therefore, the current generated by the wind turbines is also varying according to the wind velocity. The minimum adequate wind speed for wind turbines to produce electricity is 4.5–5 m/s, however, the maximum wind speed that DFIG-based wind turbines can tolerate is 25 m/s. If the wind velocity exceeds that specific value, then it will cause severe damage to the wind turbine generators. In order to protect the wind turbines from high wind speed in this article, a protective block is located to trip the wind turbine as soon as the wind speed exceeds 25 m/s to avert any potential damage to the generator and converter systems. Wind speed in this article is selected

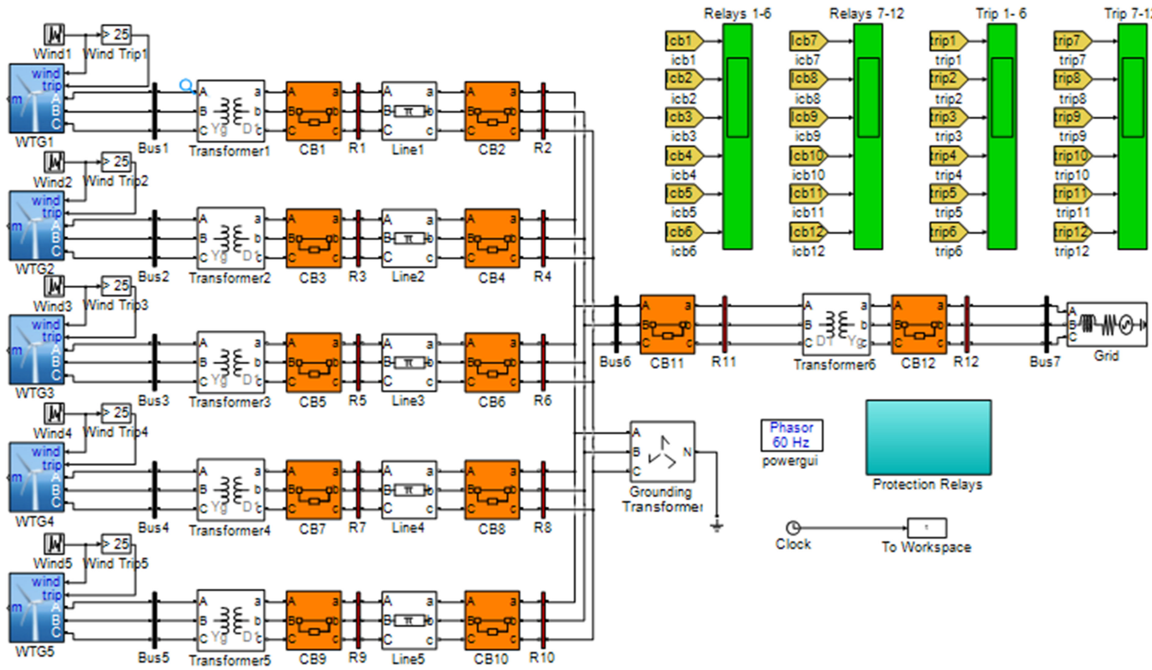

Fig. 3. DFIG-based wind farm model for the proposed protection study.

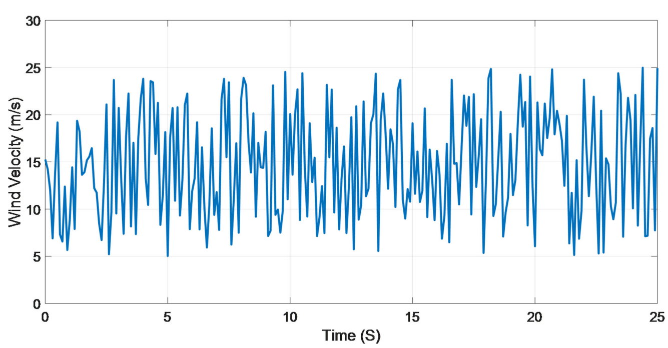

Fig. 4. Wind velocity varying from 5–25 m/s.

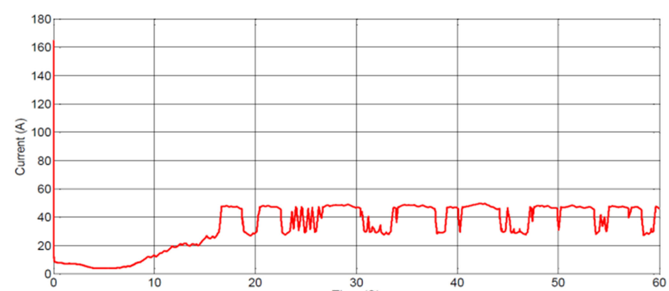

Fig. 5. Current flow through OCR12 during normal operation.

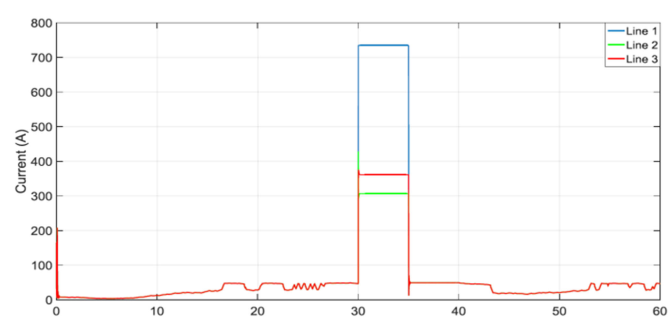

Fig. 6. Current flow through OCR12 during single line to ground fault.

to be varying in the range of 5–25 m/s. The natural variation of the wind speed for a short duration of 60 s is shown in Fig. 4 that we considered an extreme case of gust wind where the wind speed was changing rapidly. This was considered to show the application of OCR protection scheme to protect the DFIG-based wind farm in the case when wind velocity is out of the safe operating zone 5–25 m/s.

V. Simulation Results for OCR Coordination in a Wind Farm

Wind energy is an intermittent source of energy that would result in generating unstable current magnitude in wind farms. Fig. 5 illustrates the current magnitude behavior at OCR during normal operation when the farm is not exposed to any type of fault and is operating normally. Since the wind velocity is varying between 5 and 25 m/s at the mean speed of 15 m/s, the current at each OCR is also varying based on the intensity of wind that represents the intermittent nature of wind power generation.

Figs. 6–8 illustrate the current magnitude behavior at each OCR during different types of fault incidence (single line to

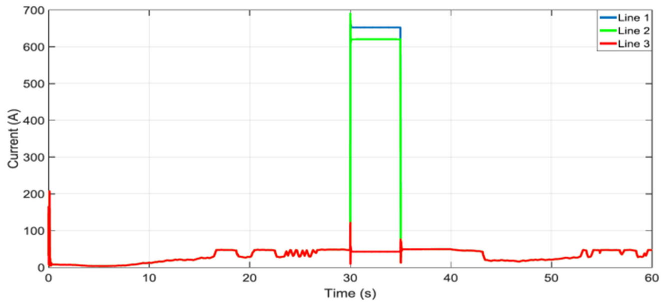

Fig. 7. Current flow through OCR12 during line-to-line fault.

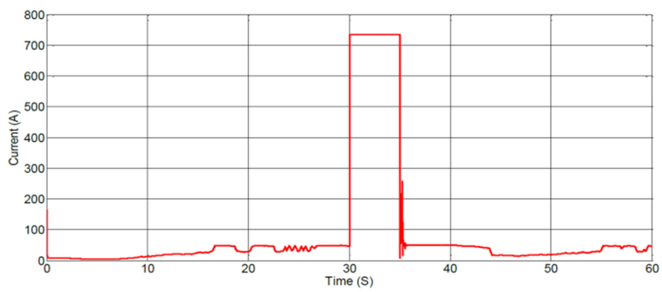

Fig. 8. Current flow through OCR12 during 3-phase fault.

ground, line-to-line, and 3-phase faults) when the farm is exposed to a fault and consequently the current magnitude drastically increases during the fault occurrence. During the simulation, fault has occurred at the 30th second lasting for 5 s near the bus on the grid side. In this article, different types of faults have been tested including both symmetrical and asymmetrical faults (i.e., 3-phase, line to line, line to line to ground, and line to ground faults) at different locations including near each bus and relay starting from the grid side to the wind turbines to examine the effectiveness and robustness of the proposed method. At time 35 s, the fault has been cleared and the wind plant operates normally afterward. It is clearly observed from the results that the current magnitude is enormously high during fault that can cause catastrophic damage to the power systems. As a result these current signals must be detected by OCRs and then tripped by CBs corresponding to respective relays to protect the wind farm apparatus.

In order for proper protection through coordination of relays to prevent this catastrophic scenario, the exact value of current and short circuit current flowing through each OCR is needed. Based on the obtained results regarding OCR settings, CB operations corresponding to respective OCR, are as illustrated in Figs. 9–12. These CB functions are based on the OCRs settings where their tripping signals based on the fault incidences shown in Figs. 13–16. In order to depict the OCRs tripping signal function more vividly, coordination of OCRs is shown in Fig. 17. In this figure, OCR12 trips exactly at time 30.1498 s when the fault has been initiated at time 30 s where the fault location is near to CB12. However, in case of OCR12 malfunction, OCR11 will trip at a longer time, which is 30.8117 s. In case that the fault location is at OCR11, then OCR11 must detect the fault and send

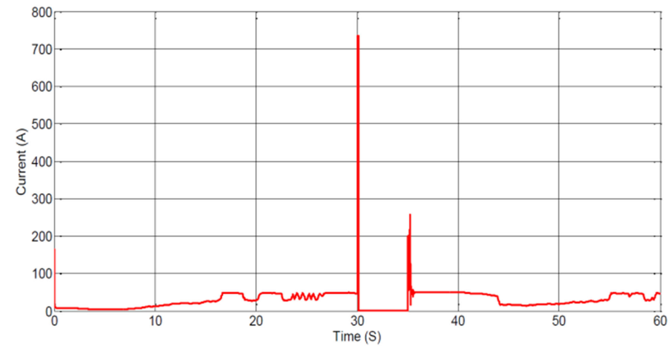

Fig. 9. CB12 operation during fault incidence.

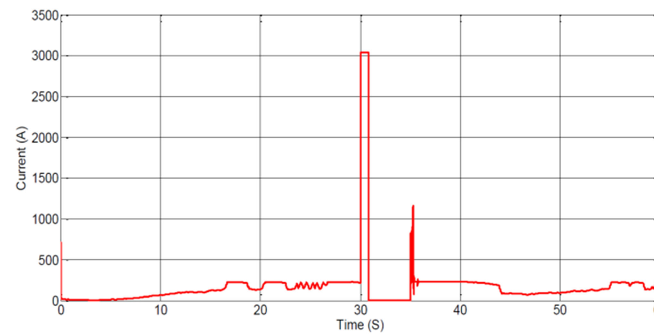

Fig. 10. CB11 operation during fault incidence.

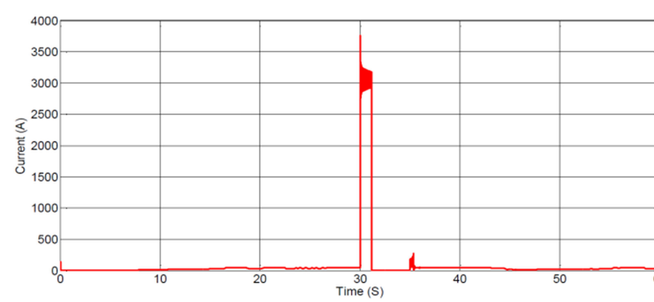

Fig. 11. CB2 operation during fault incidence.

the tripping signal to CB11. However, if OCR11 malfunction, then either OCR2, OCR4, OCR6, OCR8, or OCR10 must trip the signal at time 31.1463 s. In the case when there is a fault near OCR2, OCR4, OCR6, OCR8, or OCR10, any of these relays based on the fault location near each must operate and trip the disconnection signal to corresponding CB in order to disconnect the faulty feeder. In the case when either of these relays malfunction, then their backup relays, which are either OCR1, OCR3, OCR5, OCR7, and OCR9 must function and trip at time 31.4614 s.

Figs. 18–20 show the proposed GA-based optimized results for TSM, average distance between individuals, best and mean fitness values. The less average distance between individuals, the better the results are. Therefore, it can be clearly seen from Fig. 19 at the beginning of the simulation, the average distance between individuals were so big, which means the results

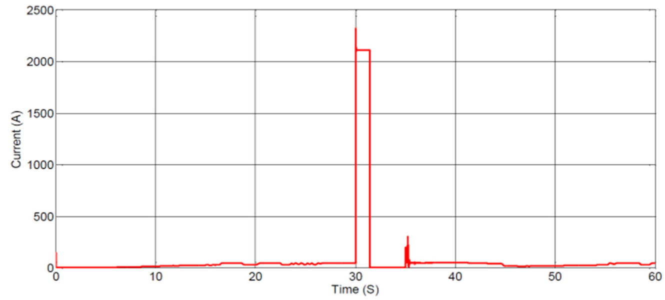

Fig. 12. CB1 operation during fault incidence.

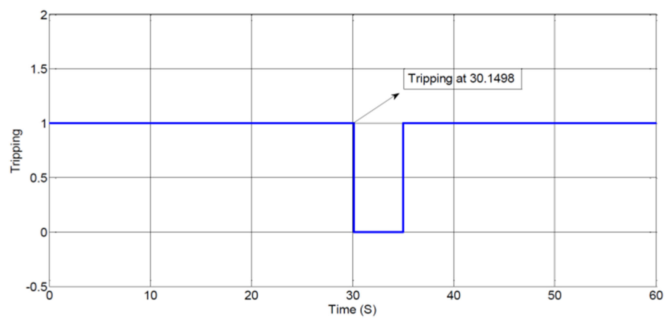

Fig. 13. OCR12 trips during fault incidence.

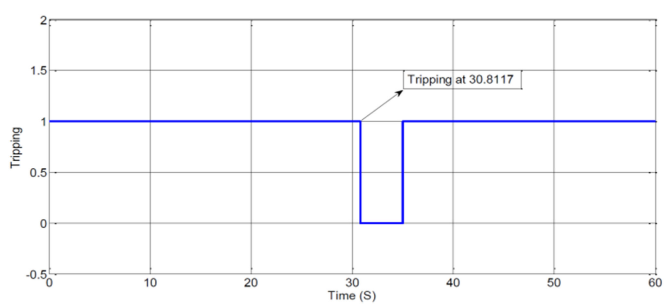

Fig. 14. OCR 11 trips during fault incidences.

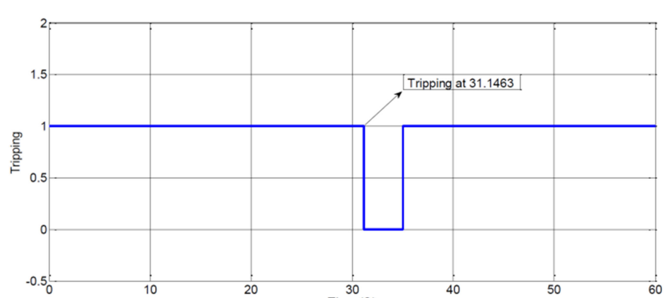

Fig. 15. OCR2 trips during fault incidence.

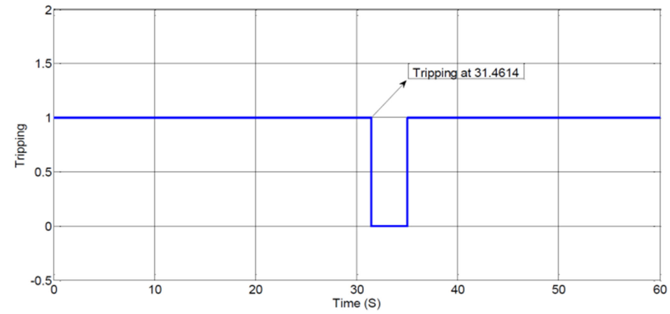

Fig. 16. OCR1 trips during fault incidence.

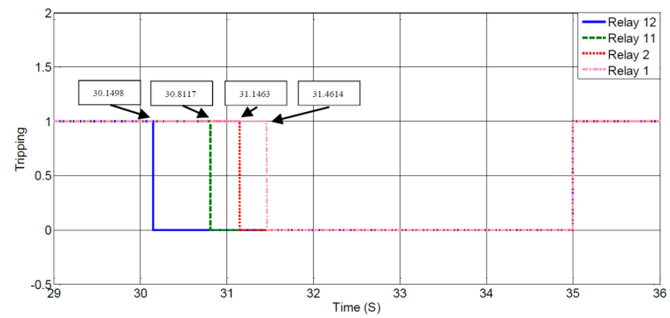

Fig. 17. Coordination of OCRs for fault occurrence.

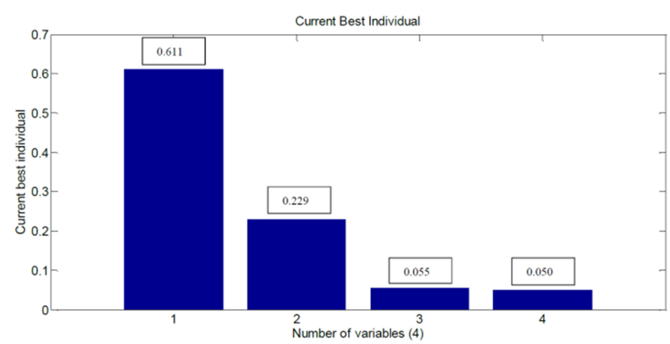

Fig. 18. Best individuals of TSM obtained by GA.

are not optimal. However, during the process, the average distance starts to diminish significantly and reach to the point where the average distance is near zero. The results have become stable and cannot become any better, and thus, the optimal values have been successfully reached. The same scenario also exists for Fig. 20, which represents the best and mean value of the objective function. At the beginning of the process the functional value is very large, however, during the process this value is decreased significantly since the GA has been trying to minimize TSM values. At the end of the simulation the OF output has reached a steady point where it cannot improve anymore. At this point, the optimal values have been successfully attained by GA and the optimal TSM values can be implemented to set the OCR operation time. Global optimal results are reached when the results are not attained any better. The GA optimization simulation is forced to stop and GA declares that the obtained results are the best and optimal values. In this article the stopping criteria has been set as "reaching highest ranking solution' fitness" and "successive iterations no longer produce better results (optimal convergence)."

After providing the OCRs with new settings obtained by GA, the same fault have been imposed to the system to test the relays

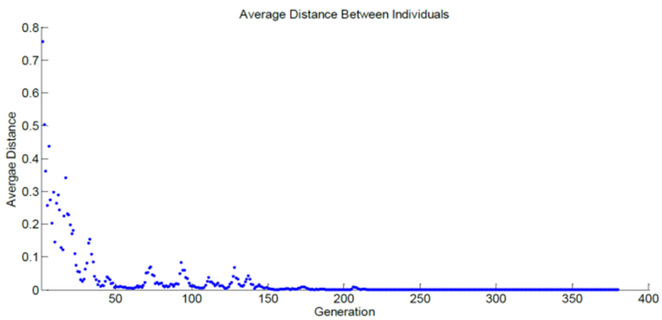

Fig. 19. Average distance between individuals attained by GA.

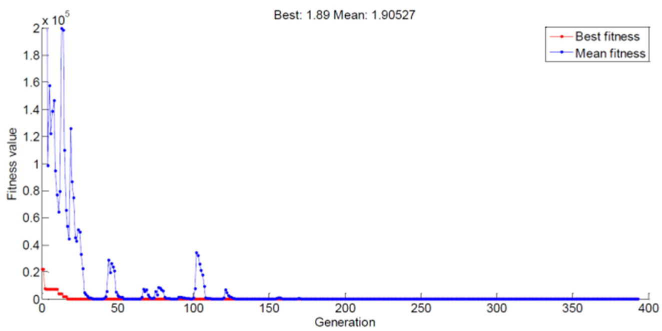

Fig. 20. Best and mean fitness values obtained by GA.

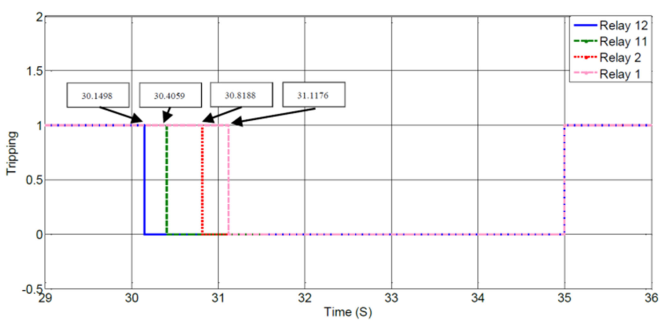

Fig. 21. Coordination of OCRs after GA implementation.

function as was done for these relays with previous conventional settings. Fig. 21 demonstrates the OCRs tripping time during occurrence of fault in the system after implementation of GA. As it can be observed, the relays operation times are significantly reduced and the relays have tripped faster due to the faults, which shows that GA has effectively optimized the OCR settings.

The OCRs settings based on conventional nonlinear time-current relay curve optimization method using IEC 60255-151:2009 standard is discussed, explained, and the relays settings calculation is determined. Moreover, their validity has also been tested and verified. A comparison between OCRs settings based on conventional method and GA optimization technique is shown in Table II. The OCRs settings in term of TSM values and operation times for the proposed GA-based optimization are drastically improved compared to the conventional optimization technique. As TSM values are reduced significantly by the GA, the operation time of the OCRs are also decreased.

TABLE II
RESULTS COMPARISON BETWEEN GA AND CONVENTIONAL NONLINEAR TIME-CURRENT RELAY CURVE OPTIMIZATION METHOD

Relay	TSM (Conventional)	TSM (GA)	T (Conventional)	T (GA)	Time Reduction Improvement
R1	0.85	0.65	1.4614	1.1176	- 23.5253 %
R2	0.35	0.25	1.1463	0.8188	- 28.5701 %
R3	0.85	0.65	1.4614	1.1176	- 23.5253 %
R4	0.35	0.25	1.1463	0.8188	- 28.5701 %
R5	0.85	0.65	1.4614	1.1176	- 23.5253 %
R6	0.35	0.25	1.1463	0.8188	- 28.5701 %
R7	0.85	0.65	1.4614	1.1176	- 23.5253 %
R8	0.35	0.25	1.1463	0.8188	- 28.5701 %
R9	0.85	0.65	1.4614	1.1176	- 23.5253 %
R10	0.35	0.25	1.1463	0.8188	- 28.5701 %
R11	0.1	0.05	0.8117	0.4059	- 49.9939 %
R12	0.05	0.05	0.1498	0.1498	0 %
Sum			14	10.2377	- 26.8735% (-3.7623s)

VI. CONCLUSION

A novel GA-based optimization technique has been developed in this article for improved protection of wind farms through proper coordination and shorter reaction times of overcurrent relays. The protection scheme has been developed based on IEC 60255-151:2009 standard. The objective function has also been formulated to achieve optimized OCR settings based on the genetic algorithm. The proposed optimization technique has been tested under various fault conditions for the developed wind farm model. The scheme is found to be capable of responding to the faults while optimizing the OCR settings effectively. Besides, the performance of the proposed GA-based optimization has been compared to the conventional nonlinear time current relay-curve-based optimization method. The proposed GA-based optimization capable of reducing the operation time of the relays by 26.8735% (3.7623 s) compared its counterpart. Hence, the proposed GA-based optimization shows significant improvement in operation of OCRs at the wind farm by achieving optimal coordination of the relays. Therefore, this article presents an effective solution for wind farm-based electrical power protection system by providing proper and optimal relay settings for prevention of the damage of power apparatus, avoidance of unnecessary power loss, and disconnection of healthy feeders out of the plant.

ACKNOWLEDGMENT

This work was supported by the Natural Science and Engineering Research Council (NSERC), Canada under the Discovery Grants-Individual Program.

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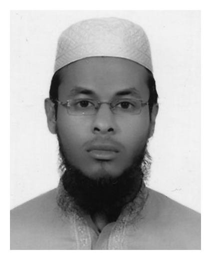

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