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 an immensely momentous aspect in electrical power protection engineering which must be contemplated thoroughly during designing the wind plants to afford a proper protection for power components in case of fault occurrence. The most commodious protection apparatus are overcurrent relays (OCRs) which are responsible for protecting power systems from impending faults. These relays are set and coordinated with each other by applying IEEE or IEC standards methods, however, their operation times are relatively long and the coordination between these relays are critical. The other common problem in wind farm protection systems is when a fault occurs in a plant, several OCRs operate instead of a designated relay to that particular fault location. This undesirable action can result in unnecessary power loss and disconnection of healthy feeders out of the plant which is extremely dire. Therefore, this research proposes a novel genetic algorithm (GA) based optimization for proper coordination of OCRs to improve their functions for protection of wind farms. GA optimization technique has some advantages over other intelligent algorithms including high accuracy, fast response and most importantly achieving optimal solutions for nonlinear characteristics of OCRs. In this work 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. It is found that the new approach achieves significant improvement in operation of OCRs at the wind farm and drastically reduces the accumulative operation time of the relays.

***Index Terms*— Wind farm, power system protection, overcurrent relay, optimization of relay coordination, genetic algorithm.**

I. INTRODUCTION

Due to the rapid growth in power demands, the ever increasing air pollution rate in addition to the decrease of unrenewable 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 energy converted to electric energy has emerged as the leader at the present time [1]. Wind power plants have been vastly employed as the means of power generation in smart grids as a distribution generation (DG) systems [2]. Undoubtedly, 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. The contribution of wind energy to power generation has reached a considerable share even on the worldwide level. Among many countries that are investing hugely on wind power generation, the top 10 leading nations in total power generation capacity are: China, USA, Germany, Spain, India, United Kingdom, Italy, France, Canada and Portugal [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 have led to emergence of some significant electrical issues including security, protection, stability, reliability and power quality. Among these issues, protection aspect plays an enormous role which needs a serious attention by researchers. Although protection of wind farms is a crucial issue that needs a huge attention, wind power plants still implement simple protection schemes which lead to different levels of damages to power components in the plant. Moreover, most of the researches conducted regarding wind farm protection have been abundantly restricted to literatures and methodologies [4]. In [5] authors reported different levels of damage but the drawbacks of the associated protection systems are occasionally mentioned. Moreover, an overall protection scheme has yet to come to solve the protection crisis in wind plants [6].

Overcurrent protection is one of the most crucial areas of protection in wind power systems. OCRs are mostly used as primary and backup protection in many regions of power networks and power plants. With the purpose of comprehensive protection, these power elements must be coordinated properly 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. Different methods of coordination have been reviewed by researchers in the past, including conventional approaches and more recent methods such as Artificial Intelligence (AI) and Nature Inspired Algorithm (NIA) [7]. However, the reported techniques are not able to attain the best possible results which is global optimization of OCR settings for wind farms. With the purpose of coordination of both directional OCRs and non-directional OCRs, optimal solutions must be provided to protect the power systems from faults in the shortest possible time. The recent trend to do so is accomplished by implementing AI and NIA in setting the OCRs' characteristics [8]. There are several methods of AI available to handle this issue, such as Fuzzy Expert Systems, Rule Based Expert Systems, Genetic Algorithm (GA) and Evolutionary Programming, Artificial Neural Network (ANN), Artificial Bees Colony (ABC), Harmony Search Algorithm (HSA), Honey Bee Algorithm (HBA) and Particle

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Swarm Optimization (PSO) [9]. Despite the massive success of GA in protection of power system components it was never used to improve the wind farm protection which is a huge gap in electrical power protection study.

As aforementioned, the increasing integration of wind power plants to power grids and their vast utilization have led to emergence of some electrical issues related to security, protection, stability, reliability and power quality. Increase in number of faults in power systems and consequently wind plant protection failures have caused further damages to power systems and accordingly hiked the costs [10]. The main problems for protection of wind farms are:

1) Improper and non-optimal conventional settings for overcurrent relays in wind farms. The coordination settings between these relays are not optimal which consequently would result in: Miscoordination in high current faults, cause crucial damages to power apparatus, and also operation of several relays, causing extended power loss, compromised power quality and stability.

2) OCR operation times are quite long that damage power apparatus, installation and endanger personnel safety.

These problems are resulted from lack of optimization in order to improve and optimize OCR settings. There are much rooms for improvement of wind plants by using GA based optimization techniques in order to reduce the operation time of relays and enhance the relay coordination.

In addressing the above mentioned problems, the main objectives of this research are:

- Improving the protection of wind farms by enhancing the coordination between relays, by way of optimizing the relay settings according to IEC 60255-151:2009 standard through the optimization of Time Setting Multiplier (TSM), and subsequently the operation time of each relay.
- Implementing 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 GA method which would consequently contribute to provide a better protection for wind farms.

Section 2 of this paper, discusses about OCRs, their function, 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 wind farm protection has been discussed in section 3. In section 4, the wind plant model for protection study has been illustrated and current flow during normal operation and during fault occurrence have been simulated as well. Section 5 has been dedicated to OCRs settings for the wind plant based on the results obtained in section 3 and 4. Beside that OCRs have been tested in order to assure their credibility and validity of relays function moreover a comparison between GA and the conventional method results has been illustrated. At the end, Conclusion has been brought to summarize all of the materials discussed in the paper.

II. OVERCURRENT RELAY

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 (less time) as the current increases. These types of relays are usually included with an instantaneous unit which causes the relay to operate instantaneously when the current reaches a high limit magnitude thus eliminating the damage to the power components [11].

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 are depicted in Table I.

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

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

In this work, in order to attain the best and actual results, the entire overcurrent relays have been successfully modelled by MATLAB software. All of the relays have been modelled 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 of 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% to 200% and in steps of 25%. This setting is only used for inverse current relays which detect phase to phase fault. For the relays that detect phase to ground fault, the PSM is quite different. It is varied in in the range of 10% to 40% in steps of 10%, or in the range of 20% to 80% in steps of 20%. The point that should be taken into consideration is that the more PSM the relay has, the higher current the relay requires to trip. 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 seconds for conventional relays, while for numerical relays it is set at 0.2 seconds, which means they operate faster compared to conventional relays [12]. 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 OCRs means that the closest relay to the fault location, which is referred to as the primary relay, must trip first 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.

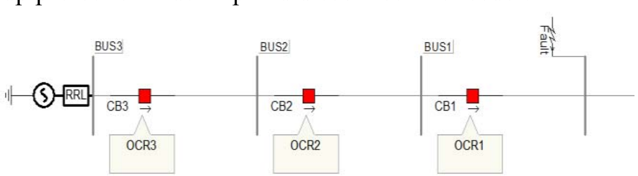

Fig. 1. Overcurrent relay coordination concept.

III. Proposed GA technique for wind farm protection

GA is an advanced and practical method that can be used for variety of applications to optimize the solutions including problems that the Objective Function (OF) is discontinuous, stochastic, and non-differentiable or non-linear [13]. GA can also be implemented for problems of mixed integer programming where some elements are constrained to be integer valued.

GA fulfill 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, that 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. In GA, several steps are taken which are described sequentially as following in Fig. 2.

Before implementing GA based technique for optimizing the OCRs coordination, a specific objective function (OF) is developed which is defined as:

$$OF = \alpha 1 \sum_{i=1}^{n} (ti)^2 + \alpha 2 \sum_{m\&b=1}^{n} \left(\Delta tmb - \beta(\Delta tmb - |\Delta tmb|)\right)^2 \quad (1)$$

The first term of OF is the sum of OCRs operation time, second term is the coordination constraint and α1, α2 and β are the weighting factors which are able to empower and increase the concentration of each section. Again, t_i represents the operating time of OCRs and Δtmb is the discrimination time between the main and backup OCRs.

The weighting factors α1, α2 and β can be customized depending on the optimization application. In every application these parameters can be changed to get the best results and optimize the relays. In this research after testing several values during GA simulation in MATLAB Toolbox, the best parameters were selected as: α1 = 1, α2 = 2, β = 100.

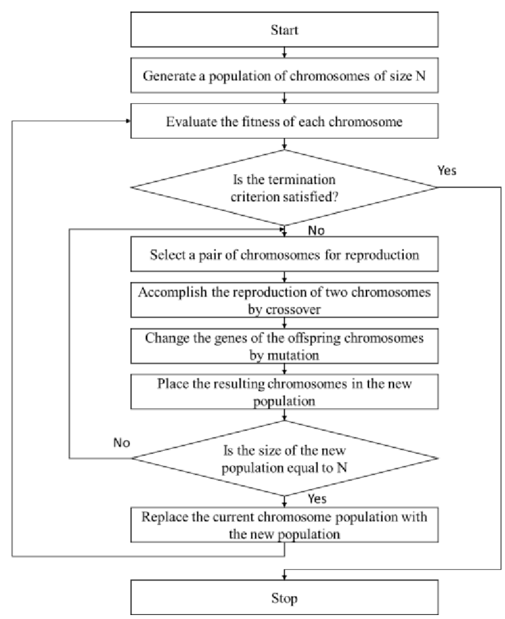

Fig. 2. Flow chart for genetic algorithm approach.

IV. Wind Farm Modelling for Protection in Matlab

There are several types of feeder topologies currently applied in wind farms. Radial, bifurcated radial, feeder-Subfeeder, and looped topologies are the most common types used, each yielding their own distinct advantages and disadvantages. These factors and other criteria such as wind profiles, available tower placement, costs, etc. must be

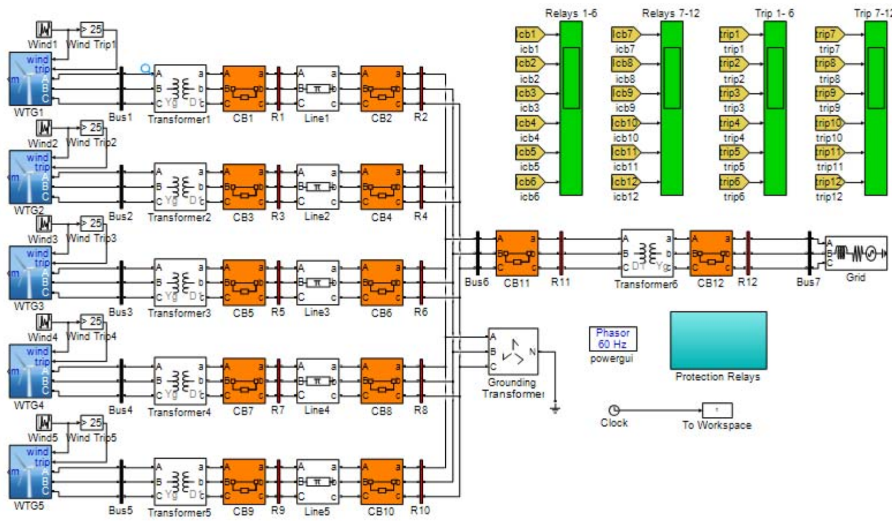

Fig. 3. DFIG-based wind farm model for the proposed protection study.

considered in order when determining which topology to use. However, the most common wind farm topology which 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 typical wind farm modelled and simulated by MTLAB-Simulink as one of the most common type of wind farm topology available in many regions is shown in Fig. 3 below. This type of wind farm based on Schweitzer Engineering Laboratories known as (SEL).

The wind power plant modelled in this research, consists of 5 wind turbines each of them produce 2 MW. Their voltage and frequency are 575V and 60 Hz respectively. Transformers corresponding to each wind turbine has voltage ratio of 575V/25KV in star delta configuration where the star side is earthed. The last Transformer corresponding to the grid has the voltage ratio of 25KV/110KV and delta star configuration where star is earthed. The transmission lines have 10 Km length each. In the figure below, since the protection area is the main scope of this research, 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 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 4.5m/s to 5m/s however the maximum wind speed that wind turbines can tolerate is 25m/s. If the wind velocity exceeds that value, then it will damage the wind turbine generators and sometimes cause fire in case of long duration of high wind speed. In order to protect the wind turbines from high wind speed in this study, a protective block is located to trip the wind turbine as soon as the wind speed exceeds 25m/s. Wind speed in this research is selected to be varying in the range of 5 to 25m/s as shown in Fig. 4.

V. SIMULATION RESULTS FOR OCRS 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. As it can be seen through these simulations, since the wind velocity is varying between 5 to 25 m/s the current at each OCR is also varying based on the intensity of wind.

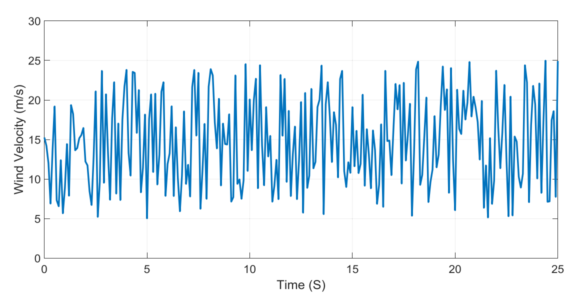

Fig. 4. Wind velocity varying between 5 to 25 m/s

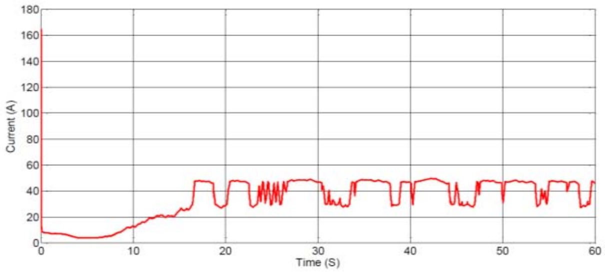

Fig. 5. Current flow through OCR12 during normal operation

Figs. 6-8 illustrate the current magnitude behavior at each OCR during different types of fault incidence (single line to 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 30th second lasting for 5 seconds. At time 35 second, the fault has been cleared and the wind plant operates normally afterward. In this study different types of faults have been imposed to this system near each relay with different locations to have the best examinations of power system relay protection. It is clearly seen from the results that the current magnitude is enormously high during fault which can cause catastrophic damages 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.

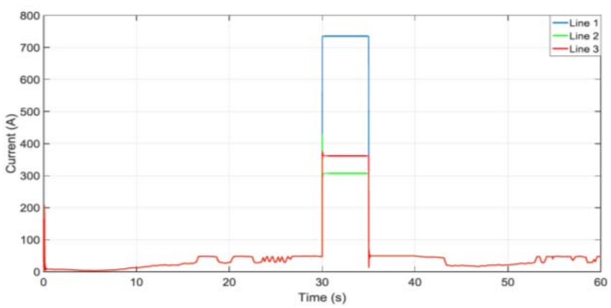

Fig. 6. Current flow through OCR12 during single line to ground fault.

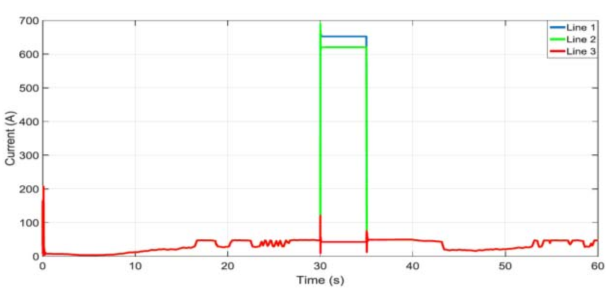

Fig. 7. Current flow through OCR12 during line-to-line fault.

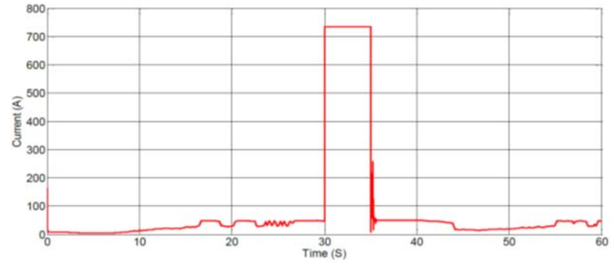

Fig. 8. Current flow through OCR12 during 3-phase fault.

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 30s 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 has to detect the fault and send 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 has to 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, OCR9 must function and trip at time 31.4614 s.

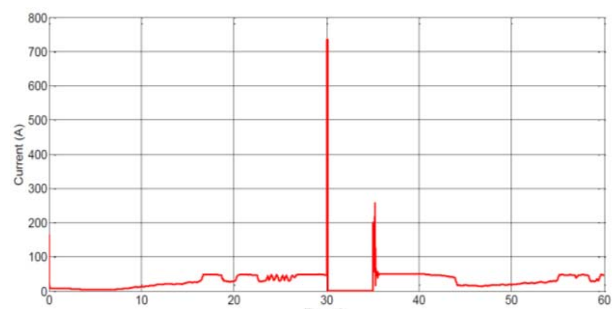

Fig. 9. CB12 operation during fault incidence

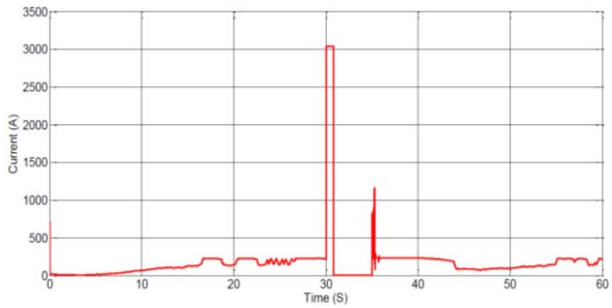

Fig 10. CB11 operation during fault incidence.

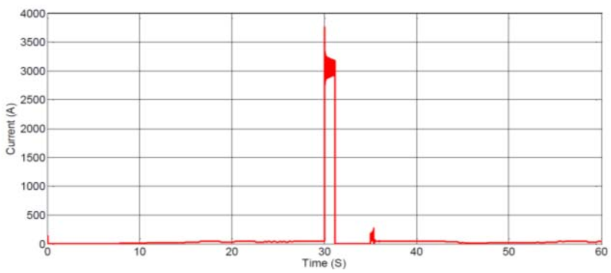

Fig. 11. CB2 operation during fault incidence.

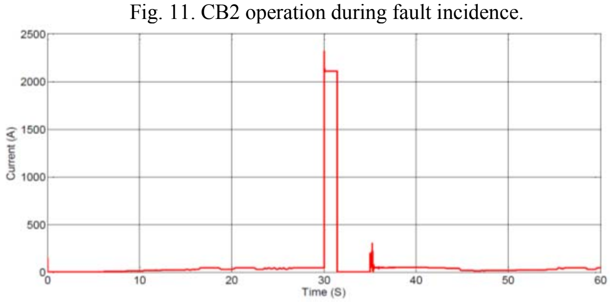

Fig. 12. CB1 operation during fault incidence

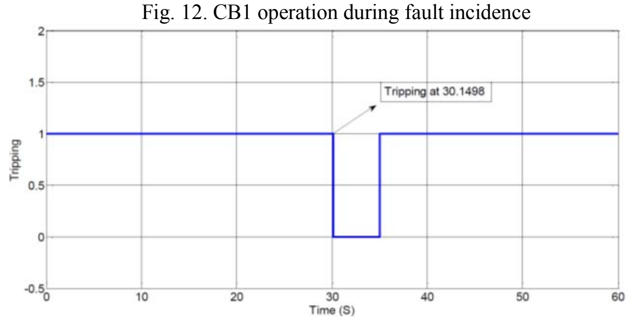

Fig. 13. OCR12 trips during fault incidence

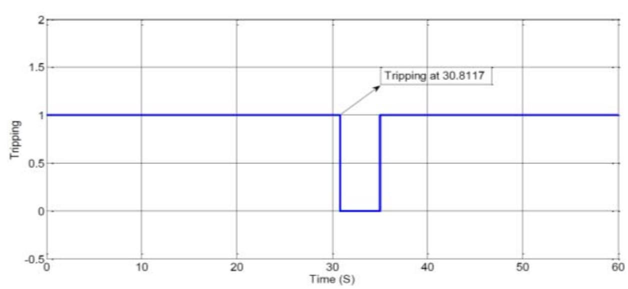

Fig. 14. OCR11 trips during fault incidence

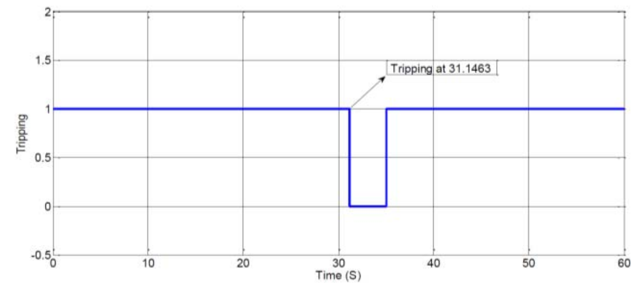

Fig. 15. OCR2 trips during fault incidence

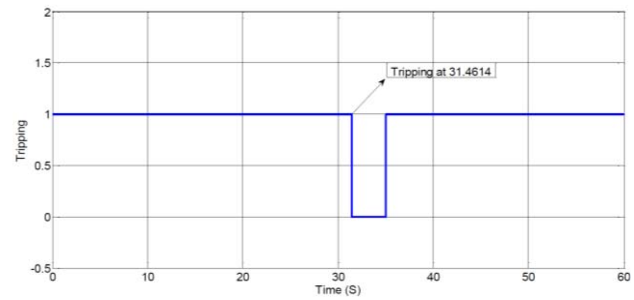

Fig. 3. OCR1 trips during fault incidence

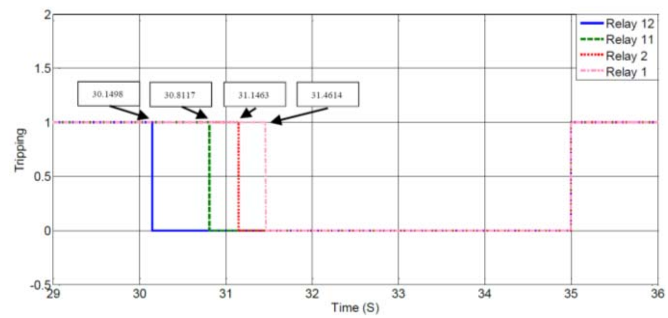

Fig. 17. Coordination of OCRs for fault occurrence

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 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. At this point the result 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 fitness function which is also called objective function. At the beginning of the process the OF 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 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. At this point, the GA optimization simulation is stopped and GA declares that the obtained results are the best and optimal values. In this work the stopping criteria has been set as “reaching highest ranking solution’ fitness” and “successive iterations no longer produce better results (optimal convergence)” which GA has successfully obtained in this study. So the optimal values that have been achieved during the GA simulation have been reached as the global optimal results and no better results can be attained anymore.

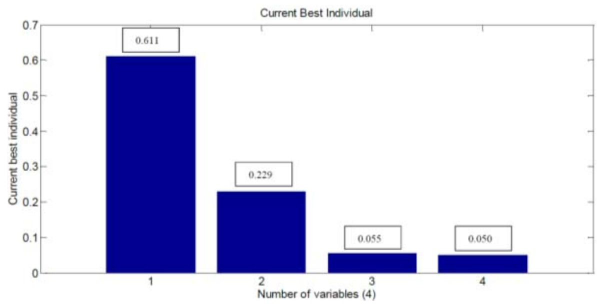

Fig. 18. Best individuals of TSM obtained by GA

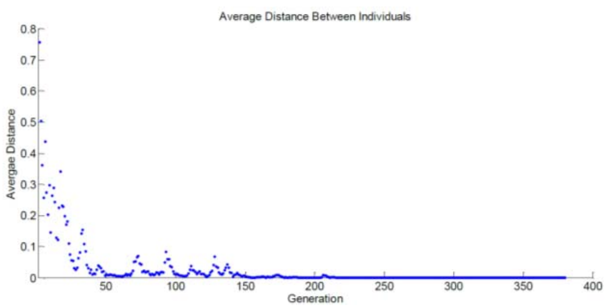

Fig. 19. Average distance between individuals attained by GA

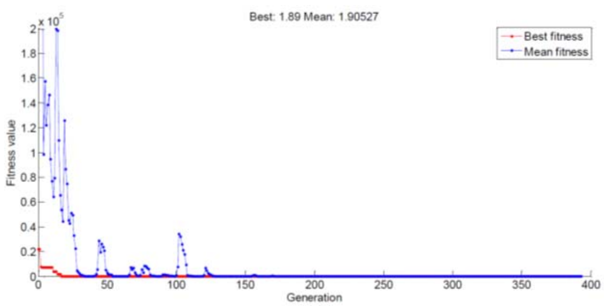

Fig. 20. Best and mean fitness values obtained by GA

After providing the OCRs with new settings obtained by GA, the same fault have been imposed to the system to test the relays function as was done for these relays with previous conventional settings. Fig. 21 demonstrate 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.

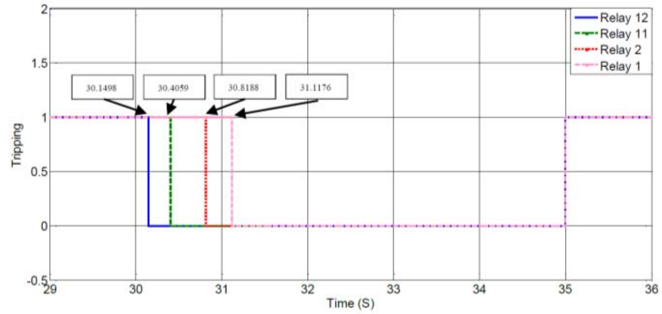

Fig. 21. Coordination of OCRs after GA implementation

OCRs settings based on conventional nonlinear time-current relay curve optimization method using IEC 60255-151:2009 standard were discussed, explained and the relays settings calculation were accomplished. Moreover, their validity has also been tested and verified. A comparison between OCRs settings based on conventional method and GA optimization technique are shown in Table II. OCRs settings in term of TSM values and operation times for the proposed GA based optimization are drastically improved compared to conventional optimization technique. As TSM values are reduced significantly by the GA, the operation time of 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 paper 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 in the presence of fault. In order for GA based optimization of OCR settings an objective function has also been developed. The proposed GA based optimization has also been compared to the conventional nonlinear time current relay curve based optimization method. The proposed GA based optimization has achieved a significant improvement in operation of OCRs at the wind farm. For example, it has drastically reduced the operation time of the relays by 26.8735% (3.7623 s) and subsequently contributed to optimal coordination of OCRs. Therefore, wind farm electrical power protection issues which were the improper and non-optimal relay settings that are causing severe damage to power apparatus, contributing to unnecessary power loss and disconnection of healthy feeders out of the plant which is extremely dire, have been successfully and effectively solved through this research.

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