Simulation of advanced STATCOM for voltage swell mitigation in large-scale test system based on swarm intelligence algorithms

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ABSTRACT. Advanced Flexible AC Transmission System is introduced in this article as a new influential technique that is applied to compensate many magnitudes of voltage swells, which is not dealt with in any research prior. One of the Advanced FACTS devices which be used in this research work is "Advanced Static Compensator", which was utilized with large-scale standard transmission networks to mitigate many voltage swells magnitudes. Most up-to-date optimization techniques like "Grey Wolf Optimization", "Whale Optimization Algorithm", and "Modified Adaptive Acceleration Coefficients PSO" were used to find out the best values of variable capacitance and gains of PI controller used in Advanced STATCOM for each voltage swell magnitude.

RÉSUMÉ. Le Système de Transmission de Courant alternatif flexible avancé est présenté dans cet article en tant que nouvelle technique influente appliquée pour compenser de nombreuses amplitudes de houles de tension, ce qui n'était traité dans aucune recherche précédente. L'un des dispositifs FACTS avancés utilisés dans ce travail de recherche est le "compensateur statique avancé", qui a été utilisé avec les réseaux de transmission standard à grande échelle pour atténuer de nombreuses amplitudes de houles de tension. Les techniques d'optimisation les plus récentes telles que "l'Optimisation de Grey Wolf", "l'Algorithme d'Optimisation de Whale" et "les coefficients d'accélération adaptative modifiés PSO" ont été utilisées pour trouver les meilleures valeurs de la capacité variable et des gains de contrôleur PI utilisés dans le STATCOM avancé pour chaque amplitude de houle de tension.

KEYWORDS: advanced flexible AC transmission system, evolutionary techniques, power quality, total harmonic distortion, voltage swell mitigation.

MOTS-CLÉS: système de transmission CA flexible avancé, techniques évolutives, qualité de l'alimentation électrique, distorsion harmonique totale, atténuation de la houle de tension.

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1. Introduction

This article investigates the effect of new introduced Advanced STATCOM device on critical power quality issue namely voltage swells over large-scale transmission networks from the mitigation effect point of view. The main idea of new Advanced FACTS devices is that, constant values of inductance, capacitance, and PI controller gains in conventional FACTS were replaced by variable values to mitigate different magnitudes of voltage swells. Most recent optimization techniques are used and compared to Particle Swarm Optimization in order to determine the best values of the variable parameters in each case. The performance of the proposed method was tested on large-scale IEEE 118 bus system using PSCAD/EMTDC software connected to MATLAB software. The results show significant enhancements in steady-state and dynamics performance of the grids by using Advanced FACTS devices as compared to conventional FACTS.

The definition of "Swell" is the rise of RMS value of voltage or current, at power frequency, to between 110% and 180% of their nominal value for duration between half cycle and one minute (Committee and Machinery, 2009). System fault conditions are not common causes of voltage swells like as in voltage sags (Dugan *et al.*, 1996). Nevertheless, one of the causes of voltage swell in the network is when a single line to ground fault (SLG) occurred in which a temporary rise of RMS voltage on the unfaulted phase can occur. The other reasons of voltage swells can be a huge capacitor bank energization, starting on large capacitive load, and shutting down a large load (Omar and Rahim, 2008).

The characteristics of voltage swells are their duration and voltage RMS value (magnitude). According to the fault location, network impedance and the system grounding, the strength of voltage swell caused by fault condition can be determined. The voltage swell effect is blowing fuses and tripping the circuit breakers due to the creation of large unbalance current, also damaging transformers, or even making malfunction or completely shutdown of sensitive equipment in plants (Edomah, 2009).

Power electronics based techniques are one of the powerful techniques used to mitigate voltage swells. In order to make the performance of the electrical networks and devices get better, Flexible AC Transmission Systems (FACTS) Technology is interested in active and reactive power management. The idea of FACTS technology includes a lot of tasks concerning with the issues faced by customers and networks jointly, mostly those problems linked to power quality, where FACTS devices can mitigate or improve a lot of power quality issues by appropriate power flow control. Depending on smart control Flexible AC, dependable very fast power electronics, and efficient analytical boxes, FACTS are offered as a most modern idea for the power systems operation and protection. FACTS can be categorized according to their connection in the network, shunt or series VAR compensators (Acha *et al.*, 2005). "Static Synchronous Compensator" (STATCOM) and "Static VAR Compensators" (SVC) are considered as shunt VAR compensators, where "Static Synchronous Series Compensator" (SSSC) and "Thyristor Controlled Series Capacitors" (TCSC) are series VAR compensators. Series compensators modify the parameters of the networks, where shunt compensators vary the impedance at the point of connection. The performance of the power system can be significantly enhanced because of the reactive power changed by both of the compensators. The construction of the traditional STATCOM consists of one voltage-source converter and a transformer connected in parallel (El-Sadek, 2004). From a technical perspective, the STATCOM is similar to the rotating synchronous condenser except it is static and it supplies or draws reactive power with a fast rate because it has no rotating parts in it.

A lot of research papers done on the conventional STATCOM regarding a type of controller used, optimal placement, and sizing for set of STATCOMs. The purpose of changing the type of the controller is to mitigate voltage sags and swells. While choosing optimal location and size for set of STATCOMs aims to improve the network voltage profile. Also some articles considered STATCOM to compensate other disturbances like voltage flickers and voltage unbalance.

PI controller in STATCOM was replaced by fuzzy logic based controller with two-input and single-output subsystem in (Flaih *et al.*, 2016) to mitigate both voltage sag and swell. Particle Swarm Optimization (PSO) was used to tune the scaling factors of the proposed controller. The experimental and simulation results show that the dynamic performance and the voltage profile of the system have been improved. In (Moghbel *et al.*, 2016), PSO algorithm was used to get the optimal location and sizing of STATCOM units connected to unbalanced 15 bus test system. The simulation results demonstrated that the voltage profile of all buses in the network can be considerably improved by appropriately allocation of STATCOM units within the system.

Multiple values of voltage sags and swells were mitigated using conventional STATCOM based on power flow solution using Newton-Raphson method in (Ulloa *et al.*, 2017). Compensating unbalanced voltage was achieved by using the Instantaneous Reactive Power (IRP) theory with STATCOM in (Pawar *et al.*, 2015). Based on (IRP) theory, load voltages and load currents were used to generate the STATCOM reference currents. The reference currents obtained were then fed to the hysteresis based PWM controller to obtain the pulses to be fed to the STATCOM. According to the obtained results, the unbalance in the system and also the harmonic components were significantly reduced. In (Muni *et al.*, 2015), STATCOM unit was used to mitigate voltage flicker. The proposed STATCOM compensates the voltage flicker completely with minimum Total Harmonic Distortion of 0.53 %.

"Advanced Flexible AC Transmission System" is introduced as a new influential technique that is applied to compensate many magnitudes of voltage swells, which is not dealt with in any research prior. The magnitude for swells is selected based on standard IEEE 1159:2009 and NTC 5000:2013. One of the Advanced FACTS devices which be used in this research work is "Advanced Static Compensator", which was utilized with large-scale standard transmission networks to mitigate many voltage swells magnitudes. Most up-to-date optimization techniques like "Grey Wolf Optimization", "Whale Optimization Algorithm", and "Modified Adaptive Acceleration Coefficients PSO" were used to find out the best values of variable capacitance and gains of PI controller used in Advanced STATCOM for each voltage swell magnitude. Also optimization techniques like "Particle Swarm Optimization", "Adaptive Accelerated Coefficient PSO", and "Adaptive Weighted PSO" were used and compared to newer ones. In order to carry out all mentioned work, MATLAB software was used with co-operation of Power System Computer Aided Design software (PSCAD/EMTDC) to develop some of previously developed modules and to offer possibility for future use of monitoring data in swell performance assessment.

The structure of the paper as follows. The proposed variations of traditional STATCOM to get Advanced STATCOM and its implementation in PSCAD/EMTDC are presented in the following section. Section three shows briefly the different optimization techniques used in this research study. In addition, two different case studies are performed in section four as well as the simulation results and discussion. Finally, conclusion of the article is introduced in section five.

2. Flexible AC transmission systems

Depending on smart control Flexible AC, dependable very fast power electronics, and efficient analytical boxes, FACTS are offered as a most modern idea to make the performance of the electrical networks and devices get better. Line impedance, voltage profile and the phase angle at specific buses can be controlled by FACTS. FACTS devices control the power flow through the network by active and reactive power management control actions of these devices. FACTS are categorized according to the used technology, where they are depending on "Thyristor Controlled Reactor" (TCR) or "Synchronous Voltage Source" (SVS), and the connection method in the power system, where they are shunted or series. One of the SVS based shunt devices is STATCOM. This section focuses on formation, function and steady state characteristics of proposed STATCOM and its implementation in PSCAD/EMTDC.

2.1. Proposed advanced static compensator

The construction of the conventional STATCOM can be found in (El-Sadek, 2004). The construction of Advanced STATCOM is similar to that of the conventional one except that the constant value of capacitive reactance is replaced by variable reactance which varies for each magnitude of voltage swell. Also PI controller has variable gains instead of constant gains in traditional controller. Variable parameters of Advanced STATOCM are changed according to the detected magnitude of voltage swell. Detection and monitoring of voltage swells occur in power networks are out of scope of this article and detailed information can be found in (Naidoo and Pillay, 2007, Zvietcovich *et al.*, 2013).

The structure of the proposed Advanced STATCOM consists of one Voltage Source Converter (VSC) with a DC energy storage device and a coupling transformer connected in parallel. A control circuit of PI controller with variable gains is also associated with the structure. Not like the conventional STATCOM, a variable storage capacitor is used here as a DC energy storage device in the proposed model. Figure1 represents the diagram of the Advanced STATCOM which is implemented in PSCAD/EMTDC. Because of the capacitor size plays an important role on harmonic distortion generation (Acha and Anaya-Lara, 2002), this work aims to identify the most suitable capacitor size for each magnitude of voltage swell in order to minimize the distortion on waveform and also keeping the transient overshooting at minimum values. Three-phase AC voltages are produced by the VSC by converting the DC voltage across the variable capacitor. These voltages are variable for each swell magnitude and are in phase and coupled with the AC system through the reactance of the coupling transformer. Suitable adjustment of the phase and magnitude of the Advanced STATCOM output voltages allows effective control of active and reactive power exchanges between the Advanced STATCOM and the AC system.

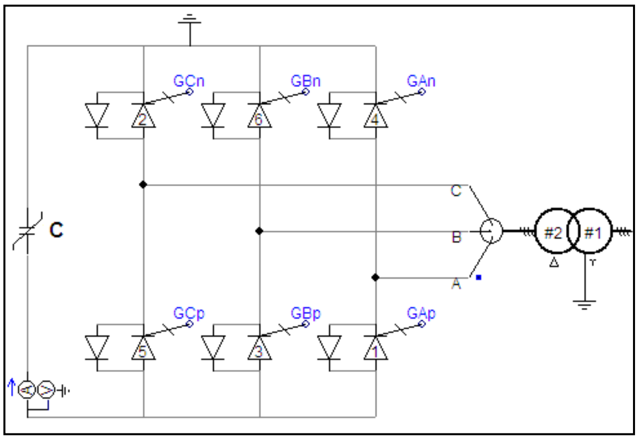

Figure 1. Structure of Advanced STATCOM implemented in PSCAD/EMTDC program

In this article, the Advanced STATCOM is used to mitigate various values of voltage swells at the connected bus. The control system depends on Sinusoidal Pulse Width Modulation (SPWM) and needs only the measurement of the bus R.M.S. voltage. The PI controller, based on variable gains, chooses the optimal gains according to the voltage swell magnitude then regulates the deviation between the actual voltage and reference voltage (i.e. 1.0 p.u.) and generates the required angle to minimize the difference to an accepted value. In the PWM generators, the sinusoidal signal is phase-modulated by means of the angle produced by the PI controller. The modulated signal is compared against a carrier signal in order to produce the switching signals for the VSC valves.

The V-I characteristic of STATCOM is indicated in Figure 2 (El-Sadek, 2004). As can be seen, the STATCOM can act as both capacitive and inductive compensators and it has the ability to separately control its output current over the maximum range of the inductive or capacitive of the network voltage. In this study, the basic principle of Advanced STATCOM used is to absorb variable reactive power for each voltage swell magnitude.

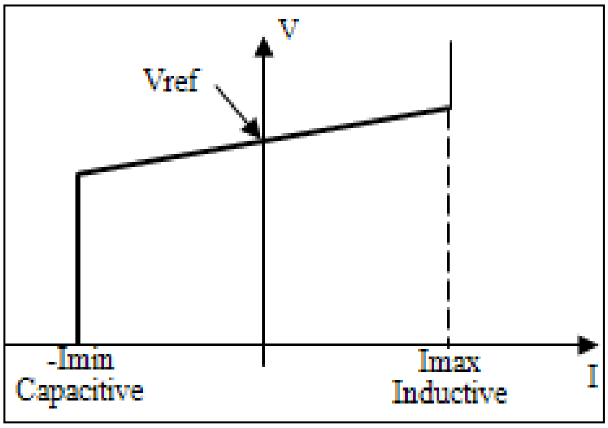

Figure 2. STATCOM V-I characteristics curve for different operating condition

3. Summary of optimization techniques used

As mentioned early, MATLAB program has been chosen to implement various optimization techniques based on swarm intelligence in order to get best values of variable capacitance and PI controller gains in Advanced STATCOM. These techniques are implemented in MATLAB program then linked to PSCAD program.

Formerly, evolutionary optimization techniques like genetic algorithm (Keshtkar, 2017) have a wide range of applications. Recently, optimization techniques based on swarm intelligence have been used in many research applications due to their better results. Furthermore, it includes: Particle Swarm Optimization (PSO) (Sundareswaran *et al.*, 2011), Adaptive Weighted Particle PSO (AWPSO) (Vidya *et al.*, 2012), Adaptive Accelerated Coefficients PSO (AACPSO) (Salhi *et al.*, 2013), Modified Adaptive Accelerated Coefficients PSO (MAACPSO) (Bahgaat *et al.*, 2016), Grey Wolf Optimizer (GWO) (Lewis and Mirjalili, 2014), and Whale Optimization Algorithm (WOA) (Lewis and Mirjalili, 2016). All the above optimization techniques were used to get the optimum capacitance values and PI controller gains.

4. Simulation results and discussion

Large-scale test system like IEEE 118 bus test system has been used to validate the introduced Advanced STATCOM. The model of test bus system with proposed Advanced STATCOM has been implemented in PSCAD/EMTDC and all optimization codes have been developed in MATLAB software. Also, the following constrains as in (1) and (2) have been added to the optimization problem in order to get the best results.

$$\textit{Total Harmonic Distortion factor (THD)} \leq 5.0\ \% \tag{1}$$

$$0.95 \leq V_k \leq 1.05 \tag{2}$$

where V_k is voltage of bus k at which Advanced STATCOM connected.

It is desirable that the bus voltage deviate from its steady-state value (i.e. is 1 p.u.) as little as possible. An error index E is proposed in (3) to indicate the transient voltage performance.

$$E = \int_{t_0}^{T} \left| V_{ref} - V_k \right| dt \tag{3}$$

where $[t_0, T]$ is the observation interval.

A better controller should result in a smaller error index, so in all optimization techniques, larger fitness will lead to better parameters. Noting that the error index is always positive, fitness function (f) is thus taken as inverse of the error index as in (4), so minimization of the error index (E) is equivalent to maximization of the fitness (f).

$$f = 1 / E \tag{4}$$

4.1. Case study: IEEE 118 bus test system

Technical data of IEEE 118 bus system is given in. During voltage swell, one bus is assumed as a sensitive bus which needs a connection of proposed Advanced STATCOM in order to compensate its voltage. The bus which has the largest load in the network is assumed as the sensitive bus which is the bus 59. Table 1 indicates the required capacitive load values that were added to the existing load on bus 59. The purpose of these modifications is to generate various values of swells. That is, the values specified here do not include the load value that is already on the system.

Table 2 presents the optimum values of the Advanced STATCOM variable parameters (variable capacitance and variable PI controller gains) along with the optimization technique leads to these results for each case of voltage swell.

Figure 3 illustrates the significant effect of the introduced Advanced STATCOM on the mitigation of voltage swell over the conventional STATCOM device. In this case, both devices were used to mitigate a voltage swell with a magnitude of 351.54 (kV) which is 1.8 (p.u.). The proposed Advanced STATCOM compensates the voltage to approximately 196.14 (kV) [1.00 (p.u.)] after 4 cycles (0.07 sec), while the non-efficient traditional STATCOM compensates the voltage to approximately 284.359 (kV) [1.457 (p.u.)].

Table 1. Load connected to bus 59 for swell generation for IEEE 118 bus system

Swell Magnitude (p.u.)	Capacitive Load (MVAR)
1.1	420.0
1.2	870.0
1.3	1270.0
1.4	1620.0
1.5	1925.0
1.6	2195.0
1.7	2435.0
1.8	2655.0

Table 2. Optimum values of Variable C, K_p, K_i, and best optimization method for each swell magnitude for IEEE 118 bus system

Swell Mag. (p.u.)	Optimum Values			Best Optimization Technique
	C [μF]	K_p	K_i	
1.1	2.0996E+03	3.5725E+02	9.5400E+00	AACPSO
1.2	2.5035E+01	3.0852E+02	1.6362E-05	GWO
1.3	2.8377E+03	5.0000E+02	3.5271E-05	MAACPSO
1.4	2.0189E+03	4.7819E+02	4.0713E-05	MAACPSO
1.5	1.5537E+03	3.4459E+02	5.6900E-05	AACPSO
1.6	9.9890E+02	2.5297E+02	7.0763E-05	MAACPSO
1.7	9.2891E+02	2.1570E+02	1.2819E-04	GWO
1.8	1.8523E+02	1.5537E+02	1.1073E-04	GWO

The dynamic performances of the Advanced STATCOM during mitigation of voltage swells with magnitudes changed from 214.79 (kV) [1.1 (p.u.)] to 351.54 (kV) [1.8 (p.u.)] are illustrated from figure 4 to figure 11. Through all ranges of swells it can be noted that, the proposed model compensates the voltage to nearly 196.14 (kV) [1.00 (p.u.)] with small overshoot value and short settling time of 0.1 sec or less.

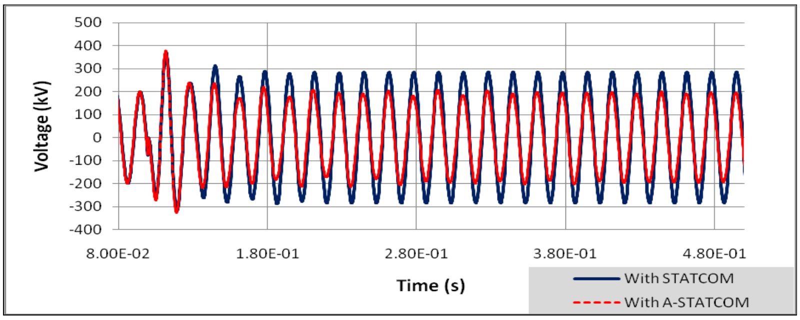

Figure 3. Comparison between traditional STATCOM and Advanced STATCOM (A-STATCOM) to mitigate 1.8 p.u. swell for IEEE 118 bus system

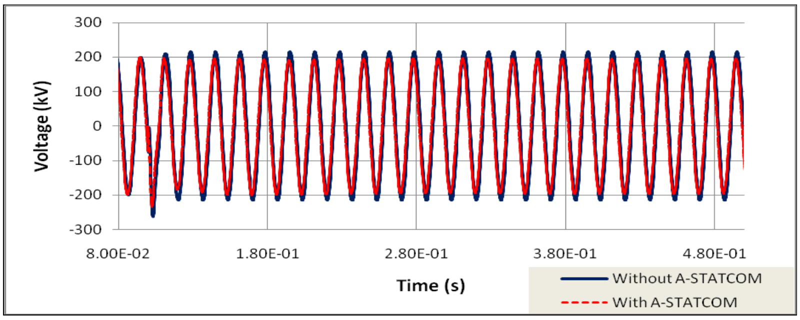

Figure 4. Mitigation of 214.7944 (kV) [1.1 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

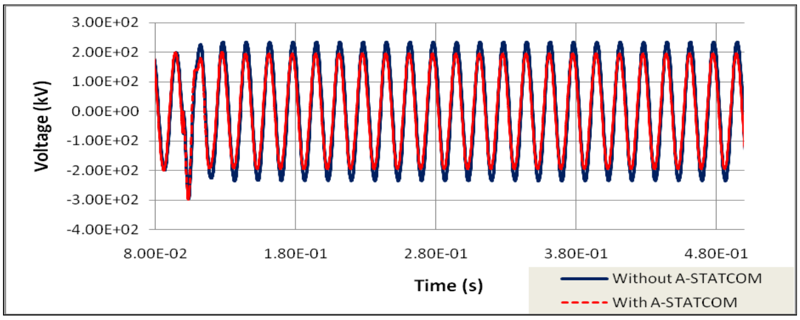

Figure 5. Mitigation of 234.504 (kV) [1.2 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

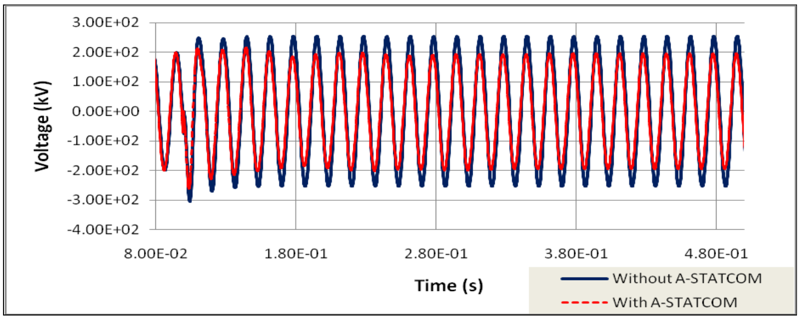

Figure 6. Mitigation of 253.948 (kV) [1.3 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

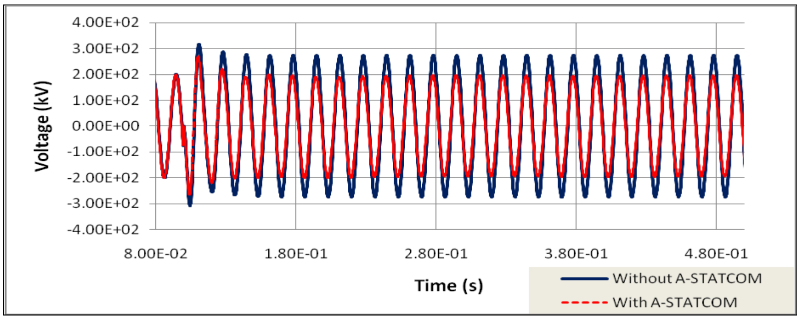

Figure 7. Mitigation of 273.524 (kV) [1.4 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

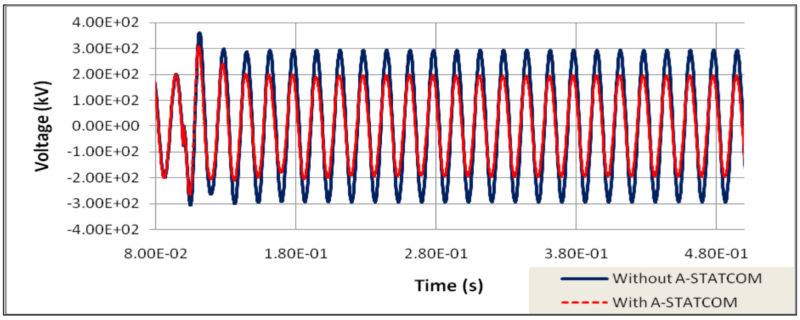

Figure 8. Mitigation of 292.991 (kV) [1.5 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

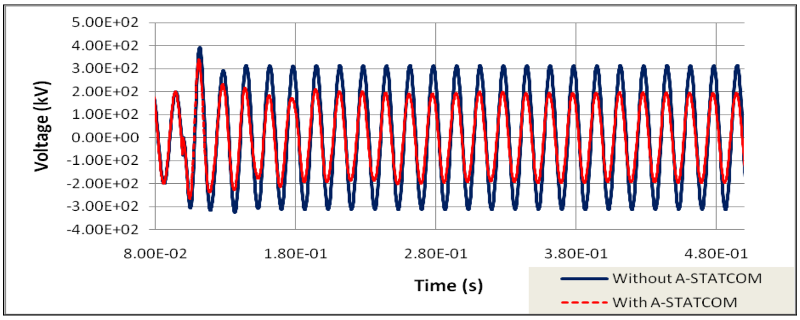

Figure 9. Mitigation of 312.436 (kV) [1.6 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

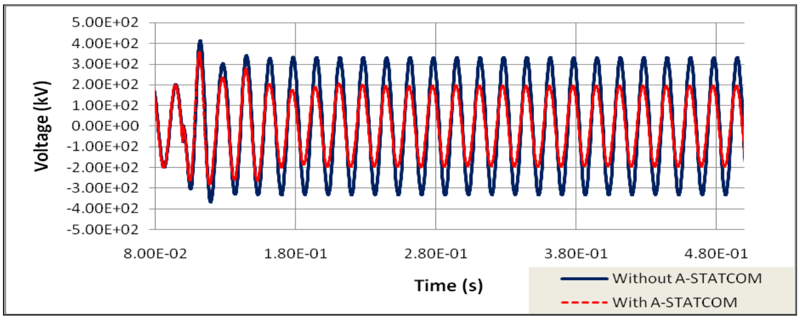

Figure 10. Mitigation of 331.803 (kV) [1.7 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

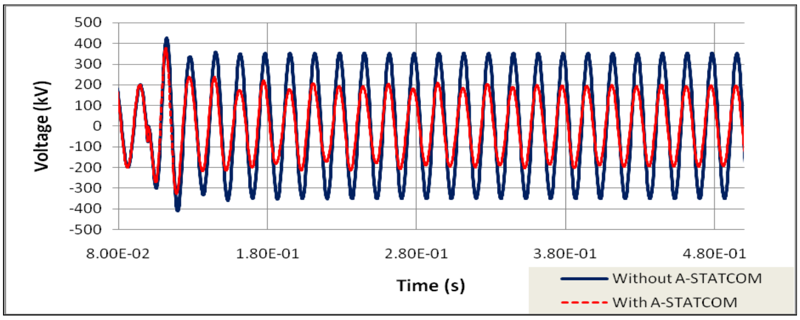

Figure 11. Mitigation of 351.54 (kV) [1.8 (p.u.)] voltage swell using Advanced STATCOM for IEEE 118 bus system

4.2. Total harmonic distortion

Total Harmonic Distortion factor (THD) is considered as one of the most familiar indices which expressing harmonic effects in voltage and current. THD can be calculated for either voltage or current as in (5) (Deilami, 2016):

$$THD = \left[\sqrt{\sum_{h=2}^{h_{max}} M_h}\right] / M_1 \tag{5}$$

Table 3. Percentage of THD in bus voltage after using advanced STATCOM for IEEE 118 bus system

Swell Magnitude (p.u.)	THD for IEEE 118 Bus System (%)
1.1	0.079130378
1.2	0.402886728
1.3	0.18403697
1.4	0.208669886
1.5	0.279763656
1.6	0.786290528
1.7	0.491792716
1.8	1.103647015

where M_h is the R.M.S. value of harmonic component h of the quantity M. THD values represented in percentage calculated for voltage of bus 59 in IEEE 118 bus system after using Advanced STATCOM for voltage swell mitigation for various scenarios of voltage swell magnitudes are represented in Table 3.

5. Conclusion

In this research work, control of the electric power system was achieved by introducing the new robust Advanced Static Compensator controller. This Advanced STATCOM was designed by making the capacitor and PI controller in conventional STATCOM to be adapted to various voltage swell scenarios by changing their values. According to the results, higher fitness values could be obtained by the latest optimization techniques likes MAACPSO, GWO, and WOA more than the newer ones like POS and AWPSO

The validity of the technique was shown by testing the model on large-scale IEEE 118 bus system using the PSCAD/EMTDC program linked with MATLAB program. The optimal location to connect Advanced STATCOM is assumed as the bus having the largest load. In order to investigate the effectiveness of the proposed controller, the proposed Advanced STATCOM was compared with the traditional

STATCOM controlled with fixed parameters. The results obtained show that the Advanced STATCOM gives excellent dynamic performance under various voltage swell magnitudes as compared to traditional one.

Total Harmonic Distortion is studied after connecting Advanced STATCOM and it is observed that the maximum THD value in all cases is 1.104 % which below 5% as recommended by IEEE standard 519-2014.

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