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Static Synchronous Compensator (STATCOM) Control for Transmission Line Voltage Swell Control

Onmoke, O., Okelola, M.O. and Aborisade, D. O.
Department of Electronic and Electrical Engineering,
Ladoke Akintola University of Technology
P.M.B 400, Ogbomoso, Oyo State, Nigeria.

Abstract
This paper shows the performances comparison of two different controllers applied to a voltage on 132 Kv transmission line incorporating STATCOM for the power quality issue of voltage swell. The first controller is genetic algorithm based Proportional Integral Derivative scheme (GA-PID) and the second controller is the Proportional Integral Derivative (PID) scheme. The sole aim of the control algorithm was to force transmission line voltage to follow the reference voltage in the event of voltage swell power quality issues. The results obtained for rise time, settling time and percentage overshoot for GA-PID and PID for voltage swell from 40 s to 90 s were 6.7 s, 10 s and 5% and 6.7 s, 40 s and 200% respectively. The simulated results shows that GA-PID presented a better performance. The successful incorporation of the STATCOM enhanced the voltage quality of the 132 Kv transmission line. The results from the analysis showed a considerable improvement in the voltage quality with the incorporation of GA-PID control based STATCOM and consequently a significant improvement of power quality at the customer's inlet point. In this way, the efficiency of the system is enhanced while the prolonged and frequent poor power quality in the transmission network are minimized.
KEYWORDS: *Voltage sag, GA-PID, STATCOM, Transmission line and PID*

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I. Introduction

The two most important aspects of power delivery system are reliability and quality. Reliability of power delivery system simply means continuity in the supply of electric power. Although, in some of the advanced countries, power generation is fairly reliable, the distribution segment is not usually so. Transmission compounds the problem of reliability further as they are the most exposed to the harsh environmental conditions [5]. However, reliability without good power quality is not sufficient in power delivery system. Hence, power quality can be defined as the ability of power system to maintain a near sinusoidal voltage waveform at the rated frequency of 50 Hz at the customer's inlet point.

To accurately achieve the desired power quality response in the case of power system voltage swell, a Genetic Algorithm based Proportional Integral Derivative control technique is employed to produce the desired specification performance of STATCOM over the conventional PID [1].

As power transmission becomes more and more complex, power electronic FACTS devices will be applied more often to ensure reliability of power system, good power quality and to improve maximum power transmission along various transmission routs.

The static synchronous compensator, STATCOM, is a shunt connected FACTS device. It generates a balanced set of three phase sinusoidal voltages at the fundamental frequency, with rapidly controllable amplitude and phase angle. This type of controller can be implemented using various topologies. However, the voltage-sourced inverter, using GTO thyristors in appropriate multi-phase circuit configurations, is presently considered the most practical for high power utility applications [5] [2]. Figure 1 shows the STATCOM connection to a utility bus. The GTO inverter shown in the figure consists of several six step voltage source inverters. These inverters are connected by means of a multi-winding transformer to a bus. The use of several inverters reduces the harmonic distortion of the output voltage [3] [4]. The inverters are connected to a capacitor which carries the DC voltage as shown in Figure 1.

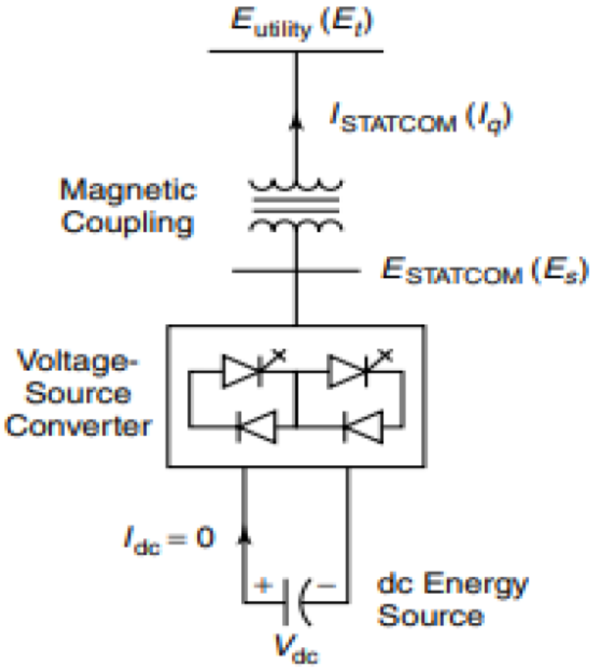

Figure 1: STATCOM Circuit Diagram

II. Materials and Method

In this section, state-space modelling equations for a three-phase STATCOM shown in Figure 2 is presented. A STATCOM state space modelling equations are analogous to an ideal synchronous machine, which generates a balanced set of three sinusoidal voltages - at the fundamental frequency - with controllable amplitude and phase angle.

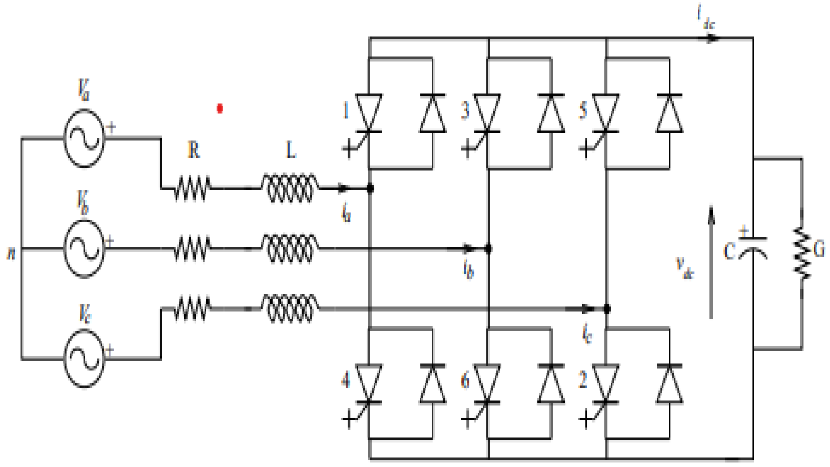

Figure 2: Six Pulse Circuit of STATCOM

Assumed that the mutual inductance between the phases is zero, the phase voltage equations of STATCOM ac side can be written as Equation (1)

$$v_{AB} = 2R(i_A - i_B) + 2L\frac{d}{dt}(i_A - i_B) + e_A - e_B$$

$$v_{BC} = 2R(i_B - i_C) + 2L\frac{d}{dt}(i_B - i_C) + e_B - e_C \qquad 1$$

$$v_{CA} = 2R(i_C - i_A) + 2L\frac{d}{dt}(i_C - i_A) + e_C - e_A$$

where:

v, i and e_s denotes the phase-to-phase voltage, phase current and STATCOM EMF respectively in the three phase *A*, *B* and *C*.

Line-to-line resistance of the circuit be denoted by $r_s = 2R$

Line-to-line inductance of the circuit be denoted by $L_s = 2L$

The sign reversal of e_B, e_C and e_A is due to moving the reference point from the common connection to ground.

Since,

$$i_A + i_B + i_C = 0 \qquad 2$$

Therefore, from Equation (1);

$$v_{AB} = r_a(i_A - i_B) + L_a\frac{d}{dt}(i_A - i_B) + e_{AB} \qquad 3$$

$$v_{BC} = r_a(i_A + 2i_B) + L_a\frac{d}{dt}(i_A + 2i_B) + e_{BC} \qquad 4$$

$$v_{CA} = -r_a(2i_A + i_B) - L_a\frac{d}{dt}(2i_A + i_B) + e_{CA} \qquad 5$$

Subtract Equation (3) from Equation (4)

$$v_{BC} - v_{AB} = 3r_a i_B + 3L_a\frac{di_B}{dt} + e_{BC} - e_{AB} \qquad 6$$

$$\frac{di_B}{dt} = -\frac{r_a}{L_a}i_B - \frac{1}{3L_a}(v_{AB} - e_{AB}) + \frac{1}{3L_a}(v_{BC} - e_{BC}) \qquad 7$$

Similarly, subtract Equation (3) from Equation (5)

$$v_{CA} - v_{AB} = -3r_a i_A - 3L_a\frac{di_A}{dt} + e_{CA} - e_{AB} \qquad 8$$

$$\frac{di_A}{dt} = -\frac{r_a}{L_a}i_A + \frac{1}{3L_a}(v_{AB} - e_{AB}) - \frac{1}{3L_a}(v_{CA} - e_{CA}) \qquad 9$$

Let,

$$v_{AB} = v_{BC}$$

$$e_{AB} = e_{BC} \qquad 10$$

Therefore,

$$v_{CA} = -(V_{AB} + V_{BC}) = -2v_{AB} \qquad 11$$

$$e_{CA} = -(e_{AB} + e_{BC}) = -2e_{AB} \qquad 12$$

Substituting Equations (10), (11) and (12) in Equation (9) yields

$$\frac{di_A}{dt} = -\frac{r_a}{L_a} i_A + \frac{1}{3L_a}(v_{BC} - e_{BC}) + \frac{2}{3L_a}(v_{AB} - e_{AB}) \quad 13$$

Using the Equations (7) and (13), the state representation of the AC side of the system is given as

$$\begin{bmatrix} \dot{i}A \\ \dot{i}B \end{bmatrix} = \begin{bmatrix} \frac{-r_a}{L_a} & 0 \\ 0 & \frac{-r_a}{L_a} \end{bmatrix} \begin{bmatrix} i_A \\ i_B \end{bmatrix} + \begin{bmatrix} \frac{1}{3L_a} & \frac{2}{3L_a} \\ \frac{1}{3L_a} & \frac{-1}{3L_a} \end{bmatrix} \begin{bmatrix} V_{BC} & -e_{BC} \\ V_{AB} & -e_{AB} \end{bmatrix} \quad 14$$

The STATCOM dc-side-circuit equation from Figure 2 can be written as,

$$\frac{dv_{dc}}{dt} = -\frac{1}{c_s}(i_{dc} + \frac{v_{dc}}{G}) \quad 15$$

The instantaneous powers at the ac and dc terminals of the converter are equal, giving the following power-balance equation as shown in equation (16): The STATCOM phasor diagram is shown in Figure 3

$$V_{dc} I_{dc} = \frac{3}{2}(v_{BC} I_{BC} + V_{AB} I_{AB}) \quad 16$$

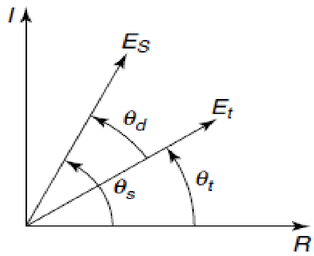

Figure 3: STATCOM Phasor Diagram

$$V_{BC} = E_S \cos\theta_s = k_{cs} V_{dc} \cos\theta_s \quad 17$$

$$V_{AB} = E_S \sin\theta_s = k_{cs} V_{dc} \sin\theta_s \quad 18$$

Where K_{CS} = is the constant relating the ac and dc voltage of the STATCOM. Therefore Equation (16) becomes

$$V_{dc} I_{dc} = \frac{3}{2}(k_{cs} v_{dc} \cos\theta_s I_{BC} + k_{cs} \sin\theta_s v_{dc} I_{AB}) \quad 19$$

where

$$I_{dc} = \frac{3}{2}(k_{cs} \cos\theta_s I_{BC} + k_{cs} \sin\theta_s I_{AB}) \quad 20$$

Substituting the value of I_{dc} in Equation. (15),

$$\frac{dv_{dc}}{dt} = \frac{-1}{c_s}(\frac{3}{2}(k_{cs} \cos\theta_s I_{BC} + k_{cs} \sin\theta_s v I_{AB} + \frac{v_{dc}}{RG}) \quad 21$$

Also, substituting the values of V_{BC} and V_{AB} from Equation (17) and (18) into Equation (14),

$$\begin{bmatrix} \dot{i}_{BC} \\ \dot{i}_{AB} \end{bmatrix} = \begin{bmatrix} \frac{-R_S}{L_S} & \omega \\ -\omega & \frac{-R_S}{L_S} \end{bmatrix} \begin{bmatrix} i_{BC} \\ i_{AB} \end{bmatrix} + \frac{1}{L_S} \begin{bmatrix} \mathrm{k}_{CS} v_{dc} \cos\theta_S - & e_{BC} \\ \mathrm{k}_{CS} v_{dc} \cos\theta_S - & e_{AB} \end{bmatrix} \quad 22$$

From Equations (21) and (22), the state-space model for the STATCOM circuit in Figure 1 can be written as Equation (23)

$$\begin{bmatrix} \dot{i}_{BC} \\ \dot{i}_{AB} \\ \dot{V}_{dc} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_S} & \omega o & \frac{1.5K_{CS}Cos\theta_s}{L_S} \\ -\omega o & \frac{-R_s}{L_s} & \frac{1.5K_{CS}Cos\theta_s}{L_S} \\ \frac{1.5K_{CS}Cos\theta_s}{L_S} & \frac{1.5K_{CS}Sin\theta_s}{L_S} & \frac{1}{R_G C_S} \end{bmatrix} \begin{bmatrix} i_{BC} \\ i_{AB} \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_s} & 0 \\ 0 & \frac{1}{L_s} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} e_{BC} \\ e_{AB} \\ 0 \end{bmatrix} \qquad 23$$

III. STATCOM Control Using GA-PID

a. Proportional–Integral (PID) Implementation

In practice, conventional proportional–integral (PID) control is typically used to control the voltage response of the STATCOM [5] [2]. PID is a generic control loop feedback mechanism. The controller has the optimum control dynamics and an impressive properties due to its simplicity, clear functionality, reliability and applicability to linear system, reduce steady state error, fast response, easy to implement, no oscillations, higher stability and robust performance. They are mostly used in more than 95% of the industrial process control application [6]. The first controller presented in this paper involves a PID control scheme. STATCOM Control using Proportional Integral (PID) Controller. The gains are the proportional, integral and Derivatives parts of the controller respectively. The PID controller is a well-known and widely use to improve the dynamic response as well as to reduce or eliminate the steady state error. PID controller consists of three types of control, Proportional, Integral and Derivatives control. The proportional (P) which is responsible for the desired set point and adjust the output controller while the Integral (I) controller adds a pole at the origin, thus increasing system type by one and reducing the steady state error due to a step function to zero.

Proportional controller*:* The proportional controller output uses a 'proportion' of the system error to control the system [7]

Integral controller: The Integral controller output is proportional to the amount of time there is an error present in the system. The Integral action removes the offset introduced by the proportional control but introduces a phase lag into the system.

Derivatives controller: Is used to improve the transient response of the systems respectively. The relationship between the input $e(t)$ and output $u(t)$ can be expressed as shown in Equation (24). The variable $e(t)$represents the tracking error which is the difference between the desired input value and the actual output. Figure 4 shows the Simulink diagram for PID control implementation

$$u(t) = k_p e(t) + k_I \int_0^t e(t)dt + k_D \frac{de(t)}{dt} \qquad 24$$

where,

Error, $e(t)$= difference between Set point and Plant output.

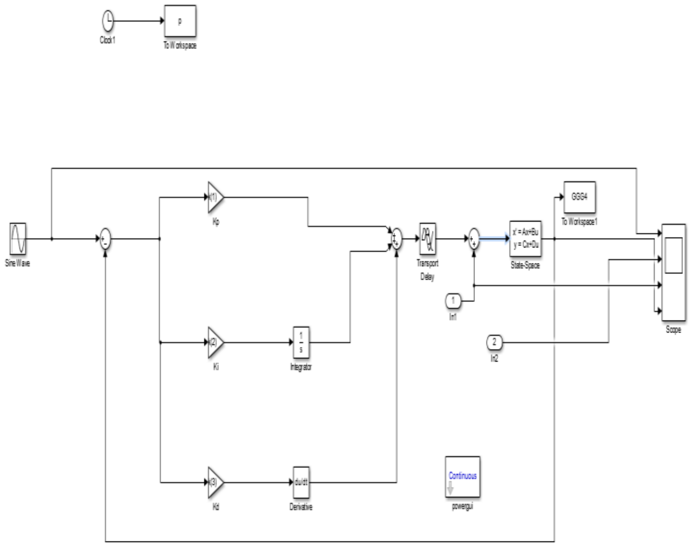

Figure 4: PID Simulink Diagram

b. Genetic Algorithm

GA as a powerful and broadly applicable stochastic search and optimization techniques is perhaps the most widely known types of evolutionary computation method today. In this paper, the GA is employed to find the best K_P, K_I, and K_D parameters. Genetic Algorithms are heuristic search algorithms based on the mechanics of natural selection, genetics and evolution. [3], [9].

4.1 Genetic algorithm procedure

The main procedure of applying GA's to search the optimum parameters of the controller's include: [10] [7]

3.1.1 Encoding:

The first step in applying GA's to the selection of STATCOM controller parameters is Encoding, which maps the parameters of the controller's into a fixed-length string.

3.1.2 Fitness Computation:

According to the comprehensive design objectives as mentioned above.

3.1.3 New Population Production:

New populations are created using three operators: Reproduction, Crossover and Mutation. Reproduction is a process in which individual strings are copied according to their fitness value. Reproduction directs the search toward the best existing individuals but does not create any new individuals. The main operator working on the parents is Crossover, which happens for a selected pair with a crossover probability. Multi-point crossover has been applied to solve combinations of features encoded on chromosomes. Although Reproduction and Crossover produce many new strings, they do not introduce any new information into the population. As a source of new bits, mutation is introduced and is applied with a low probability.

3.1.4 Stopping Criterion:

If all of the objectives are met, the generation cycles will terminate. Otherwise, go to step (3.1.2) and compute the fitness for each population.

3.1.5 Decoding:

This process converts binary alphabets into digital numbers, which gives meaning to the strings, after which the controller parameters are finally determined. The Genetic Algorithm (GA) is depicted in the form of a flowchart shown in Figure 5. The main standard for genetic algorithm includes the following four operators. GA selection is a selection operation that will select the parent solution. During the reproductive phase of GA, individuals are selected from the population and recombined, resulting in offspring which in turn will comprise the next generation. The crossover takes two parents and cuts the parent chromosome string at several randomly selected positions, to produce two "head" segments and two "tail" segments. The mutations are applied to each child individually, after the crossover.

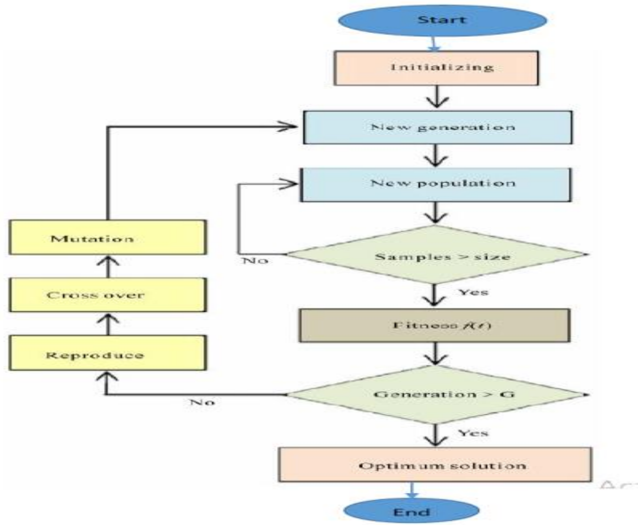

Figure 5: Genetic Algorithm Flow Chart

The basic block diagram of the system is shown in Figure 6. In order to tune the parameters of PID controller through genetic algorithm, the k_P, k_I and k_D are taken and the chromosome is formed. The main objective of the study is to minimize the error between the input and the plant's output.

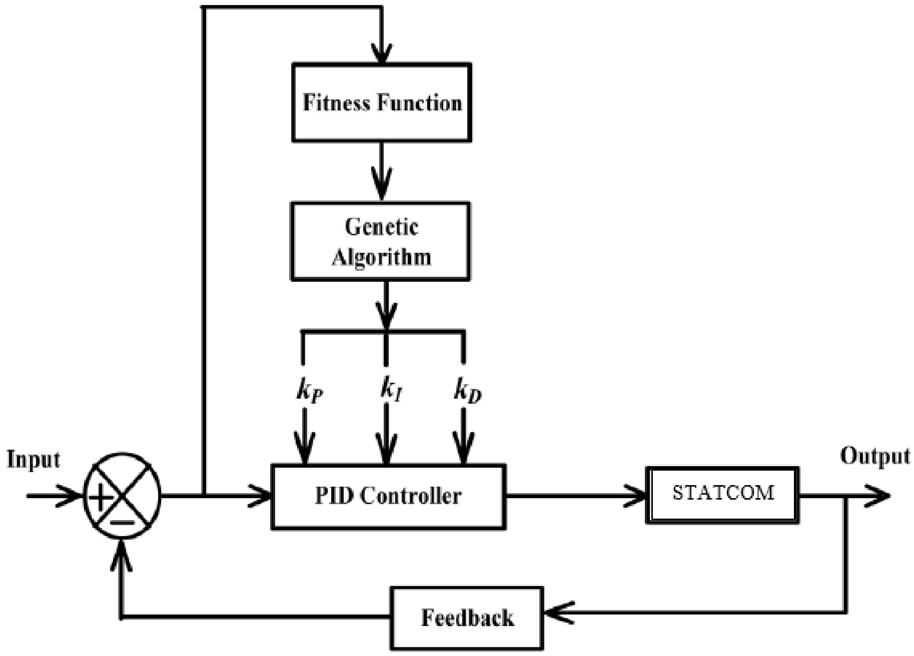

Figure 6. Basic block diagram of GA based PID controller [28].

GA Operators for tuning the PID parameters are shown in Table 1, STACOM parameters are shown in Table 2 while Simulink diagram for GA-PID implementation is shown in Figure 7.

Table 1: the GA Operators for PID

Parameters	Specification
Number of generation	120
Population size	50
Mutation probability	0.1
Crossover probability	0.2
Chromosome length	21

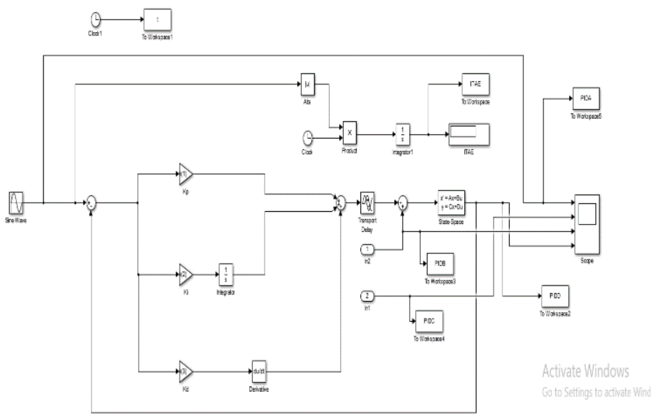

Figure 7: GA-PID Simulink Diagram

Table 2: STATCOM Data

Parameters	Value
Power	5MVA
Series line resistance	0.1301 Ω
Series line reactance	2.42 Ω
DC-link capacitance	750 µF
G	128 Ω
Theta	180 degree

IV. Results and Discussion

Using the general voltage equation expression, the maximum voltage value was increased from 1pu to 1.5pu at the frequency of 50Hz from 40 s to 90 s duration to produce voltage swell signal. This voltage swell served as a disturbance input signal to the genetic algorithm based PID and the conventional PID controllers. The results obtained for rise time, settling time and percentage overshoot for GA- PID and PID for voltage swell from 40 s to 90 s were 6.7 s, 10 s and 5% and 6.7 s, 40 s and 200% respectively. GA-PID shows a better performances for settling time and percentage overshoot when compared with CBEMA requirements for voltage swell

To evaluate the performance of the system, a series of measurements has been accomplished. The performance results of PID and GA-PID for voltage swell are shown in Table 3. The performance results of PID and GA-PID controllers of STATCOM were plotted in Figure 8 and Figure 9 respectively. Figure 10 shows the combined response of both PID and GA-PI response against the reference voltage. The following characteristics, Rise Time (t_r), Settling Time (t_s) and percentage overshoot (M_p) against CBEMA curve were considered for validation as shown in Table 3 for rise time, settling time and percentage overshoot respectively

Table 3: Performance Result of GA-PID and PID Control based STATCOM for Voltage Swell from 40 s to 90 s

Metrics	GA-PID	PID	CBEMA
Rise time	6.7	6.7	-
Settling time	10.0	40	≤ 60
%overshoot	5.0	200	≤ 10

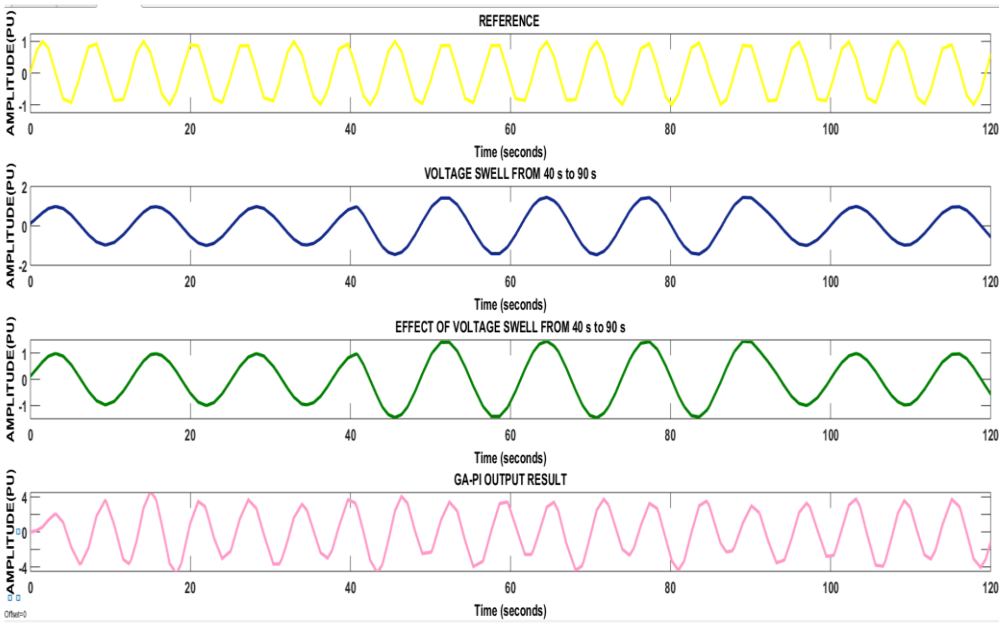

Figure 8: GA-PID Control based STATCOM Output for Voltage Swell from 40 s to 90 s

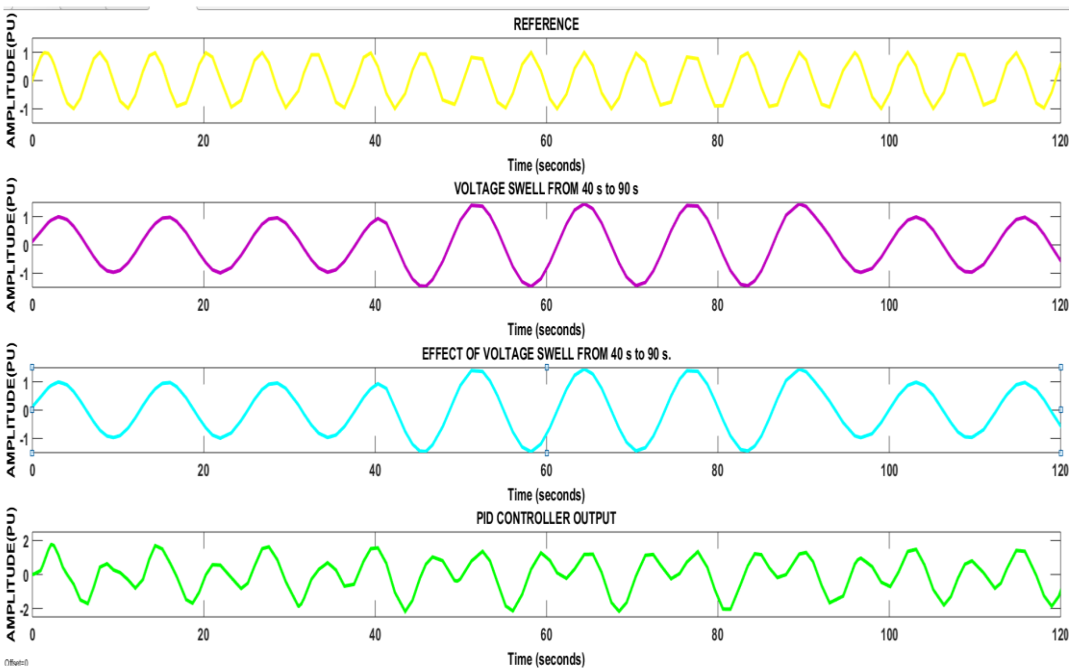

Figure 9: PID Control based STATCOM Output for Voltage Swell from 40 s to 90 s

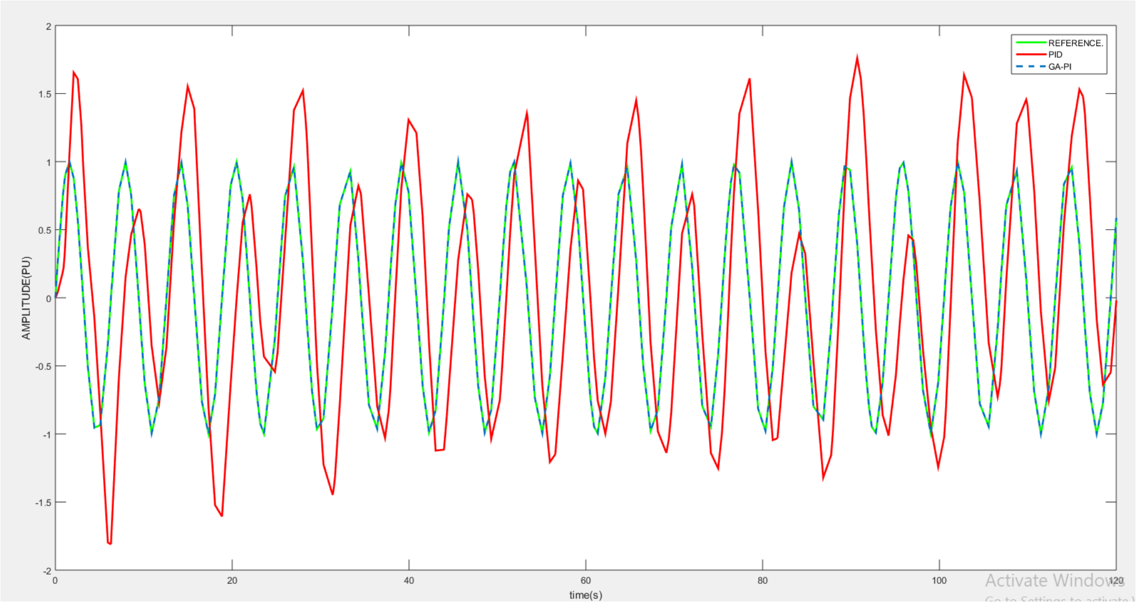

Figure 10: PID and GA-PID Control based STATCOM Output for Voltage Swell from 40 s to 90 s

V. Conclusion

The modelling of a three phase STATCOM for power quality enhancement applications is presented in this paper. GA-PID and PID types of feedback controllers are developed and compared using rise time, settling time and percentage overshoot for voltage swell Power Quality issue. It was observed that GA-PID outperformed PID

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