review

Novel Design to Tune SVC for Power Factor Correction and Reactive Power Control Using Cascaded ANN Approach (CANNA)

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Abstract: This article introduces new method using ANN to control SVC in order to correct the source power factor of low voltage network. Two ANN approaches are investigated to design accurate and fast power factor correction (PFC) controller. First approach uses simple ANN (SANNA). Second approach uses cascaded ANN (CANNA). ANN regression, performance and the calculated error for both approaches are investigated to select between the two approaches. CANNA is selected as a better solution and it used to build the ANN PFFC controller using database, generated by MATLAB-Simulink, for standard three low voltage levels (240V, 220V and 110V). Nine test cases are carried out to validate the performance of proposed ANN PFC controller with a network has variable loads and low power factor (0.6 approximately). In order to extend the use of the controller to other voltage levels not included in the training process of the cascaded ANN, only the SVC is resized. Another nine cases are carried out with the same loads using the same ANN controller, as it is, to test its performance with the extended voltage level range (415V, 230V and 120V). The results show accurate and fast response in all test cases.

Keywords; power system; reactive power control; power factor correction; arterial neural network

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1. Introduction

Active power is the amount of power that is actually usable, and it is known also as Real Power, while reactive power is the part of complex power that corresponds to storage and retrieval of energy rather than consumption. Apparent power is the vector sum of real power and reactive power. Power factor at the source is the ratio of the delivered real power to the apparent power consumed by the total connected load.

When power source is connected to the network, different loads with different power factor values consume active and reactive power from the source. As a result, power factor at the source varies with loading [1].

One of the negative consequences of the low power factor is the higher current that will flow through the network. This higher current results in a greater voltage drop across the OHTL's and cables, especially if these line are marginally sized and/or very long. For loads connected to the same network with constant power such as motors, this voltage drop causes additional increase in the current. This results an energy loss due to heat dissipation from cables and transmission lines. This energy produces exponential temperature rise with time in the cable conductor material and insulators. If the generated temperature rise rate is relatively high in such way that the heat dissipation from the cable is less than the heat rise in the insulation, this may cause by time degradation of the insulation electrical properties. If the thermal overload cause is not eliminated in a very short time, the cable insulation will damage, whish result faults and downtime in the electrical network. Which can be translated into cost, loss of production and dissatisfaction to the clients. Therefore, a poor power factor can contribute to equipment instability and failure, as well as significantly higher than necessary energy costs since it means that more current is required to perform the same amount of work. By optimizing and improving the power factor, power quality is improved, reducing the load on the electricity distribution system. [2-6].

Another negative consequence of low power factor is on the electrical equipment sizing. It causes the electrical equipment, such as cables, transformers and generators to be selected for larger than their rated values. In another meaning, low power factor reducing

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the production capacities of the electrical equipment, and limit the capacity of transmission and distribution lines [7,8]. In order to get rid of this effect, the power factor needs to be corrected.

In many countries, the clients are charged not only for their active power consumption, but also for their reactive power demand. This extra amount is because of the low power factor. The power factor penalty is an incentive for the customer to pay attention to the power factor at their operation and consider installation of power factor correction capacitors rather than pay a penalty.

From all the above, it is necessary to improve the power factor to improve the power system quality and to reduce the operational costs. An ideal power factor would be 1.0. In ac network, it is impossible maintaining a perfect power factor of 1.0 without using Power Factor Correction (PFC) system. This can be simply achieved by adding a controlled capacitor banks in parallel to the loads. However, there is other more complex methods such as synchronous condensers are also used [9]. But, capacitor PFC modules become nowadays an essential building blocks of any industrial AC power distribution network to ensure minimum downtime or breakdowns in the machinery [10].

Artificial intelligent techniques such fuzzy logic, artificial neural network and generic algorithms are used widely in reactive power control and power factor correction for different application such as single phase power factor correction and converters power factor [11-14]

In case the power factor that is needed to be corrected varies with loading, PFC capacitor bank needs to be switched between its different stages to achieve the correct amount of positive reactive power from the capacitor that compensates the negative reactive power consumed by the load. A special control is required always when design such switching system for capacitor to consider the overvoltage transient and to limit the inrush current [15,16].

The most common structure of Static Var Compensator (SVC), is a parallel combination of controlled reactor and fixed shunt capacitor. The thyristor switch assembly in the SVC controls the reactor. The firing angle of the thyristor controls the voltage across the inductor and thus the current flowing through the inductor. By this way, the net reactive power draw by the SVC can be controlled, and hence the power factor can be smoothly corrected and improved [17-19].

Focusing in Artificial Neural Network (ANN) application in power factor correction, ANN is used efficiently with different method to design intelligent controllers. In [20], the paper used fitting ANN algorithm to predict suitable duty cycle is to guide and control the DC-DC converter to reduce the phase shift between grid voltage and grid current as possible to have maximum PF which is unity PF. The algorithm used 2 input (Grid voltage and Theta) and one output (Duty cycle). The paper introduced power factor controller for specific converter size, and cannot be used, as is, with different converter size. For another controller, the same procedure and validation need to be repeated. In [21], the paper used clustering ANN technique to improve the power factor of electrical generation. This is approach is an optimizing approach rather than actual reactive power control to improve the power factor to unity. In [22], ANN has been applied to adjust power factor correction automatically. The results obtained indicate that the implementation of ANN has a better performance than the conventional method for tackling the problem, has closer value to the set point value. However, the results were not satisfactory as in many cases the controller failed tom improve the power factor to a point higher than the set point. In [23], SVC, that is based on ANNs controller, is employed to the proposed case study system in order to reduce the computational time of finding the optimum firing angles. The neural control system has three inputs which are the 3-phase load reactive power. The output of ANNs is the optimal firing angles that are calculated from GSA algorithm.

In this article, Cascaded ANN (CANN) is used with SVC to tune the voltage of the reactor, and hence control the total reactive power at source, in order to improve the power factor at source for the connected single phase variable load. The article considers exactly the same controller unit to be used with different standard low-voltage levels of power source. In section II, the rating of electrical load and SVC are introduced. Section III provide the steps that were followed to build the ANN PFC controller. Section IV illustrates the ANN PFC controller performance, its test cases and discuss the results. The summary and conclusion are given in Section V.

2. Electrical Load, SVC Rating and Generation of Database

A group of eight inductive loads with different ratings and low power factor of approximately 0.6 are used to model single phase circuit powered from LV source. This power factor of 0.6 is practical value for aggregated inductive loads that are connected to low voltage distribution circuit [24]. These load are switched on to the power source in sequence in specific time intervals.

As Power Factor Correction (PFC) usually be required where a system has a power factor of less than 0.9[25], therefore the capacitor and the reactor of the SVC that is used to correct the power factor is sized to supply the required reactive power that can correct the power factor to unity.

The circuit configuration is illustrated in Figure 1 and the load rating are listed in Table 1.

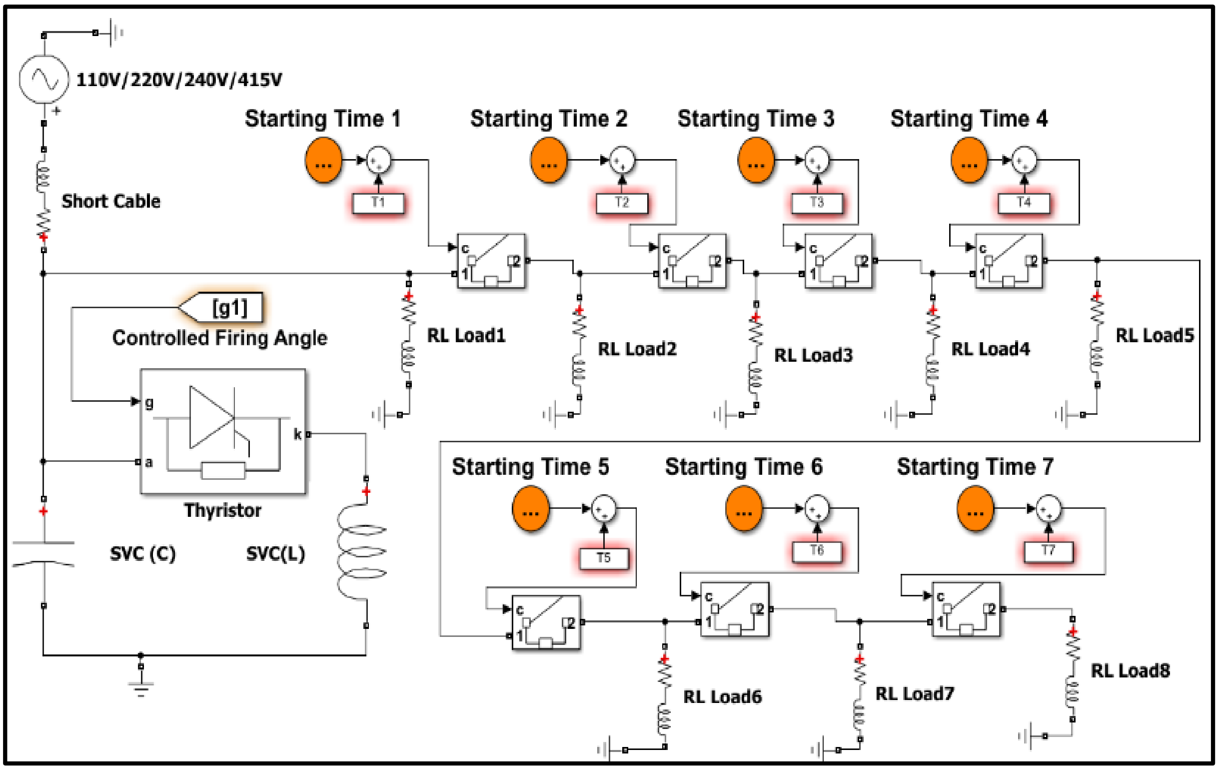

Fig. 1: Single phase circuit with SVC

Table 1: Loading rates

Interval	Loading stage	Load Type	Base Voltage	Active Power kW	Reactive Power kVAR	Power Factor
T0	Load 1	R L Series	240	2.25	3	0.6
T1	Load 1 + 2	R L Series	240	6.75	9	0.6
T2	Load 1+2+3	R L Series	240	18	24	0.6
T3	Load 1+2+3+4	R L Series	240	48.375	62.5	0.6121
T4	Load 1+2+3+4+5	R L Series	240	78.75	103	0.6074
T5	Load 1+2+3+4+5+6	R L Series	240	95.625	125.5	0.6061
T6	Load 1+2+3+4+5+6+7	R L Series	240	105.75	139	0.6055
T7	Load 1+2+3+4+5+6+7+8	R L Series	240	111.375	146.5	0.6052

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From the above table, in order to insure power factor equal to one is achieved for all loading stages, the SVC capacitor and reactor need to be selected with rating higher than 146.5 kVAR each, calculated at base voltage of 240Volt, in order to compensate the maximum reactive power of the load when the firing angle is 180º. The nearest standard rating for the SVC component is 150kVAR. This gives approximately 2.3% extra reactive power margin stored in the SVC that may be required to compensate any reactive power consumed in short cable.

3. ANN PFC Design:

By tuning the firing angle of the thyristor, the voltage across the reactor can be adjusted to control the reactive power delivered from SVC.

Equation (1) and (2) give the general formulas for the r.m.s value of reactor current (I_{SVC-L}) and voltage (V_{SVC-L}) respectively:

$$I_{Load} = \frac{\sqrt{2} \times V_{source}}{z} [\frac{1}{\pi} \int_{\pi}^{\beta} \{\sin(\omega t - \theta) - \sin(\alpha - \theta) e^{(r/l)(\alpha - \omega t)}\} d\omega t]^{1/2} \quad (1)$$

$$V_{Load} = \frac{V_{source}}{\pi} (\beta - \alpha + \frac{\sin(2\alpha)}{2} - \frac{\sin(2\beta)}{2})^{1/2} \quad (2)$$

Where:

$\omega = 2\pi f$ radian/second

α = Firing angle

β = Extinction angle (cut-off angle)

$\theta = \tan^{-1} (l/r)$

l = Load Inductance

r = Load Resistance

t = Time

z = Load impedance.

Since the conducting angle $\delta = \beta - \alpha$ cannot exceed π, the firing angle α may not be less than θ and the control range of the firing angle is $\pi \geq \alpha \geq \theta$ [26-27] .

The SVC reactive power at any fining angle can be calculated using Equation (1 and (2), however, iterative method using MATLAB-Simulink tool can be used as a practical and fast method to determine the relation the reactive power that can be obtained from the SVC (from 0-150kVAR) at any firing angle value between 0^{O} and 180^{O} [28- 29]. Fig 2 illustrates the proposed Simulink model that will is used to build the required database for the ANN PFC:

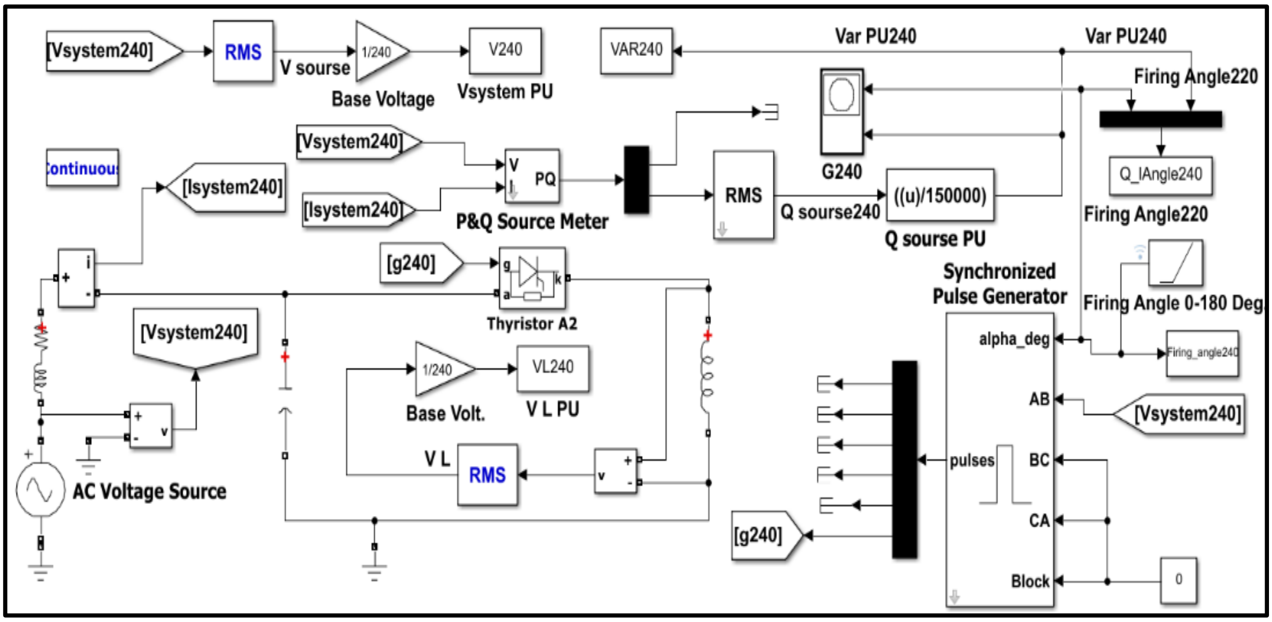

Figure 2: Simulink Model to obtain the required database for ANN PFC

From this Simulink model, reactive power (Q_{SVC}) that can be obtained from SVC and the voltage across the reactor (V_L) can be determined for any firing angle (α) value and for any selected source voltage (V_n).

This model is used to obtain Q_{SVC} and V_L for α from 0-180^O for three different standard nominal voltages for source, 240V, 220V and 110V as main data base to build the ANN PFC controller. Figure 3 and Figure 4 illustrate the result.

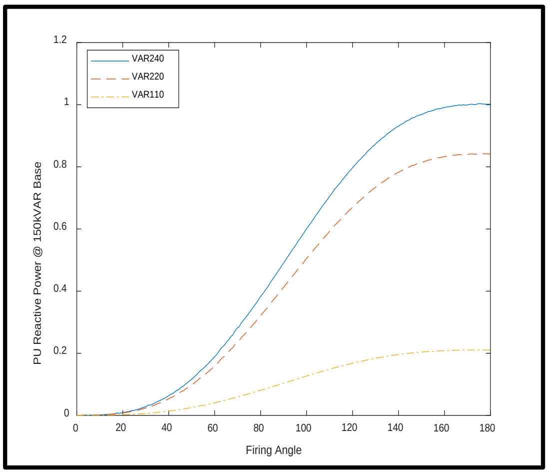

Figure 3: Q_{SVC} for different Voltage levels

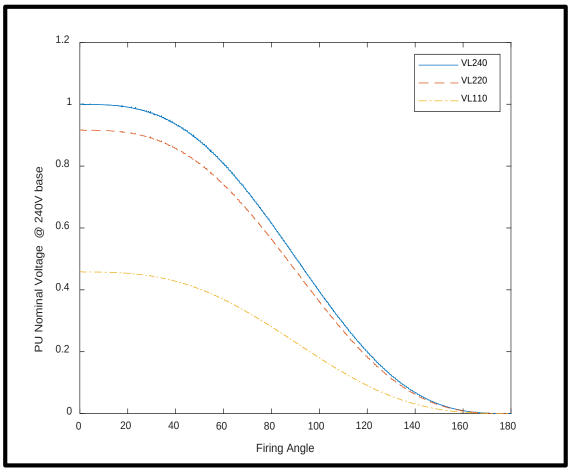

Figure 4: V_L foe different voltage level

4. ANN model

The PFC controller has to compensate accurately the reactive power that required to correct the power factor to preset value. This can be achieved by measuring the reactive power at source, and determine the required reactive power that need to be compensated to achieve the preset power factor value, then trigger the SVC with the proper firing angle to produce the correct Q_{SVC}.

Regardless the voltage level that can be different than 240V, 220V, and 110V, if the connected load has the same maximum reactive power, the proposed ANN PFC control unit needs to be still usable for any other low voltage level.

In the design of the proposed ANN PFC controller, two input signals are used, source nominal voltage and SVC reactive power Q_{SVC}, and the output signal (Target) from the ANN controller is the firing angle. In order to achieve the best possible results for

ANN training to design the PFC controller, two different approaches were investigated. First approach uses single ANN, however the second approach uses two cascaded ANN.

A. PFC based on Single ANN approach (SANNA):

In this approach, the database obtained from Figure 3 is used to train the ANN. The structure of ANN includes one hidden layer with 20 nodes. The training input matrix includes 2x218091elements. The training output vector includes 218091 elements, test input matrix includes 2x21809 and the test output vector include 21809 elements. MATLAB default criteria to terminate the trials in the training process is use. Figure 5 illustrate the ANN structure that are used in training the algorithms. Figure 6 shows the Regression results and the Performance.

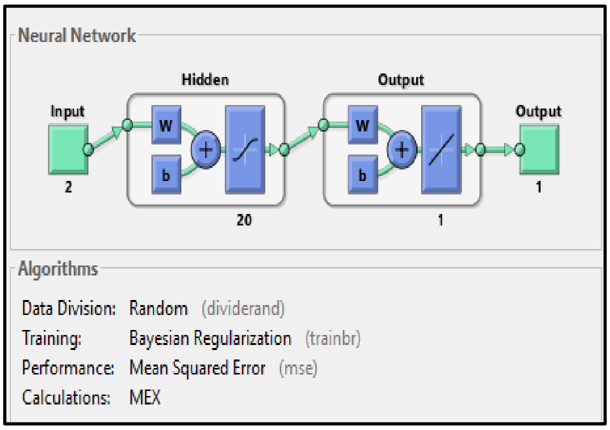

Figure 5: Structure for SANNA

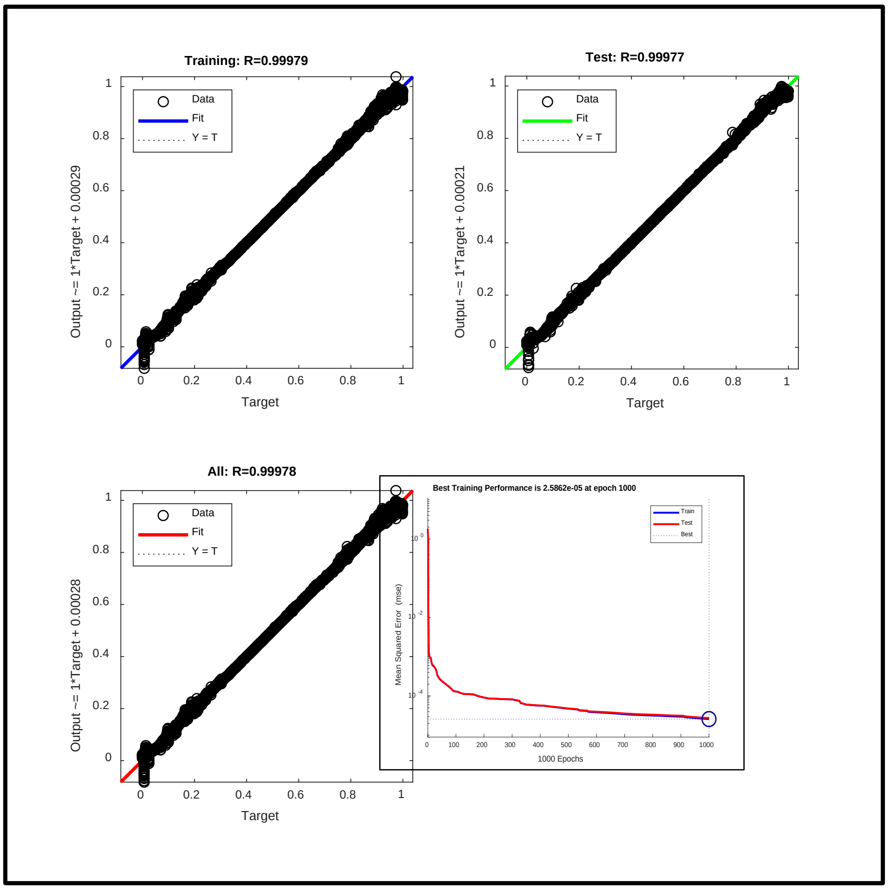

Figure 6: Results for SANNA

B. PFC based on Cascaded ANN Approach (CANNA):

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Figure 3 gives a relation between Q_{SVC} and α for different nominal voltage levels. Figure 4 gives a relation between V_L and α for different nominal voltage levels. Based on these two relation, it is obvious that direct relation between Q_{SVC} and V_L can be obtained using ANN.

In cascaded approach, the voltage across the reactor (V_L) obtained from an intermediate trained ANN that its input signals are Q_{SVC} and nominal voltage (Vn), and its output signal is the estimated (V_L). Then this V_L output is used as an additional input to train input the next ANN which its input signals are Q_{SVC},V_n and V_L, and it output signal is the firing angle (α). Figure 7 illustrates the structure of the cascaded ANN that will be used to build the PFC controller.

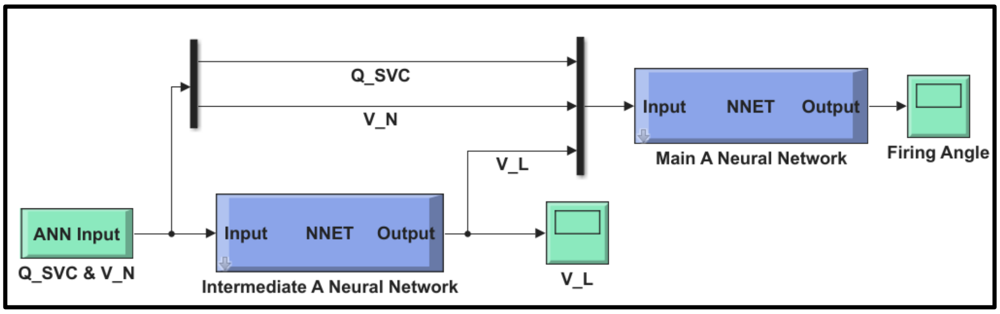

Figure 7: Structure of CANNA

To be able to compare the results correctly between SANNA and CANNA, same algorithm with same number of epoch is used, Figure 8 and Figure 9 illustrate the Regression results and the Performance results for the intermediate ANN and Main ANN respectively.

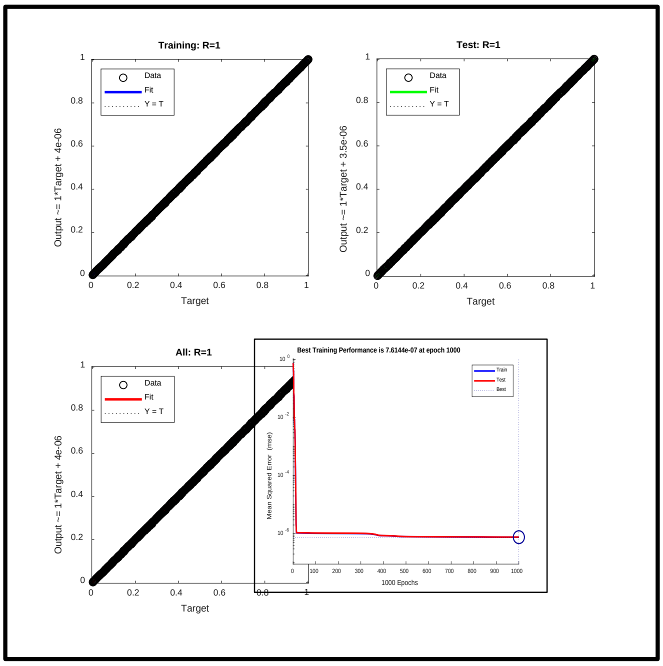

Figure 8: Results for Intermediate ANN for CANNA

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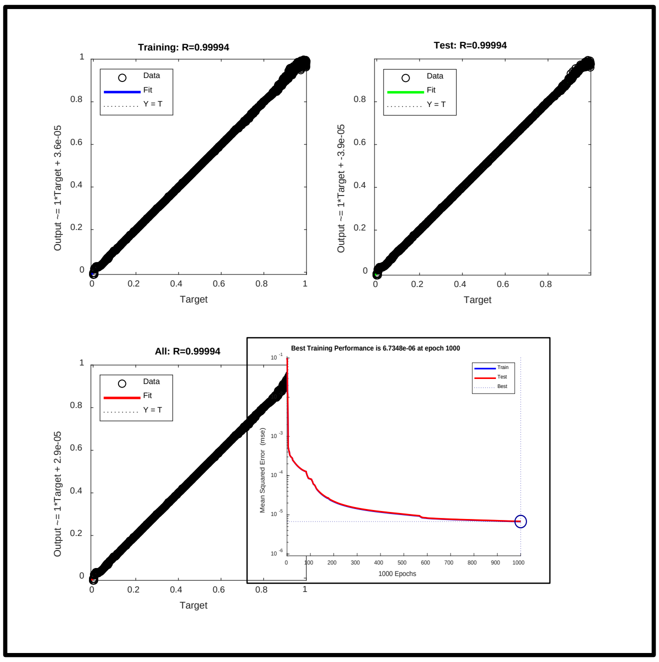

Figure 9: Results for Main ANN for CANNA

The performance results indicated in Figure 6, Figure 7 and Figure 8 show that for both Intermediate ANN and Main ANN in CANNA, better performance is achieved compared with the performance of SANNA. By Comparing the ANN regression of SANNA with the Main ANN of the CANNA, it is shows that for CANNA the regression is better, which indicates that error is less comparing with SANNA, considering that Intermediate ANN regression is 1 and it will not contribute in the error value.

Figure 10 and Figure 11 illustrate the errors for SANNA and CANNA. From these two graphs, the results show that the maximum error in SANNA is 0.08968 however the maximum error in Cascaded Approach is 0.03653.

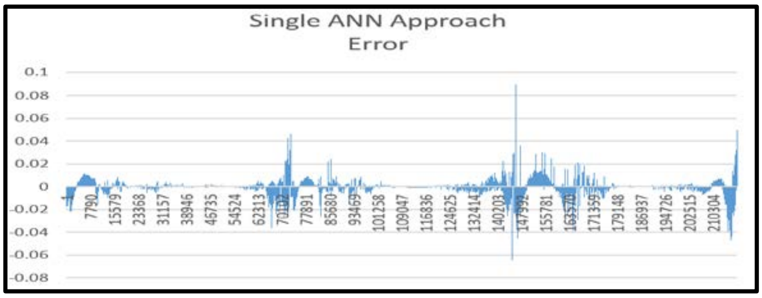

Figure 10: Error Results for SANNA

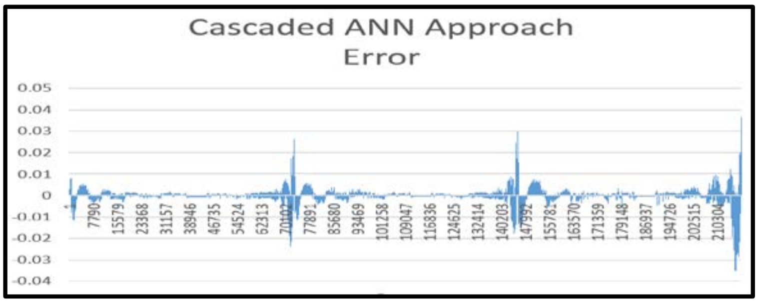

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Figure 11: Error Results for CANNA

From the above results and analysis, it can be concluded that CANNA is better than SANNA, hence it will be selected to be used to build the ANN PFC controller.

5. ANN PFC model and Results

The ANN PFC controller based on CANNA is connected to the single phase load circuit that illustrated in Figure 1. The complete Simulink circuit is illustrated in Figure 12.

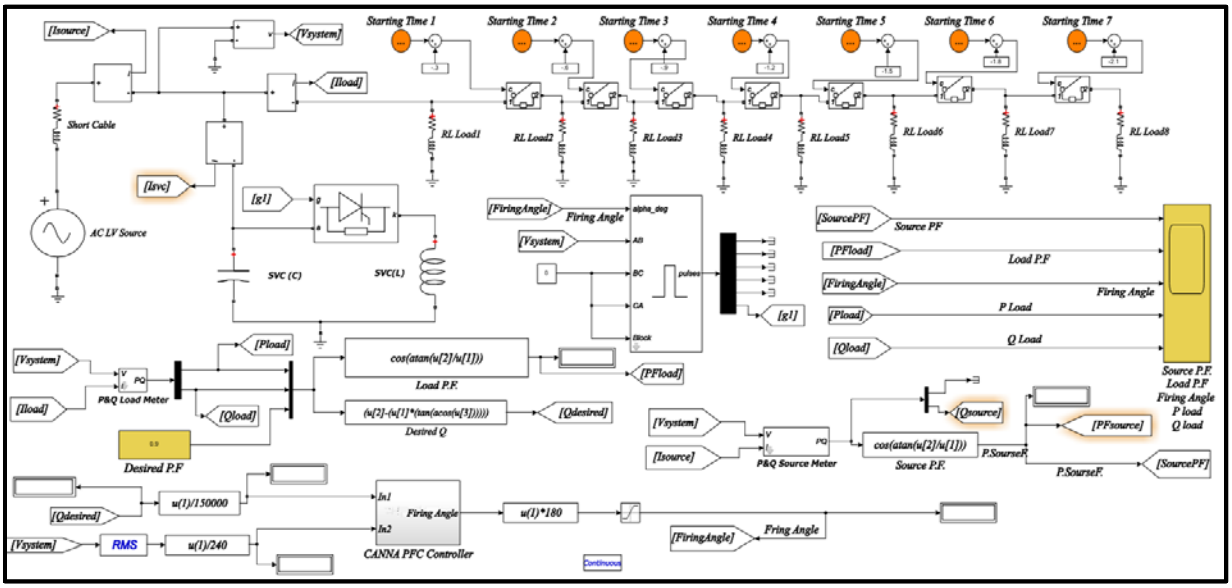

Figure 12: Complete Simulink circuit with CANNA PFC

In order to validate the performance of the CANNA PFC controller, two groups of tests are carried out. The first test is to validate the controller performance in correcting the power factor to achieve different preset values using the same source voltages that were used in the ANN training process. The second test is to verify the capability of using the same controller, as it is, using voltage levels different than the values used in the training process. The chosen voltages for Group 2 test cases covers the standard nominal low voltage values higher and lower to the base voltage of Group 1 (240Volt). Table 2 lists the test cases for the First Groups. In this test cases, the SVC rating is kept without change calculated at 240V base voltage.

Table 2: Group 1 test cases

Group No.	Base Voltage (Volt)	Source Voltage (PU)	SVC Base voltage (Volt)	SVC Rating (kVAR)	Desired Power Factor	Results Figure
1	240	1	240	150k	1, 0.95, 0.9	Fig. 13, Fig. 14, Fig 15
1	240	220/240	240	150*220/240	1, 0.95, 0.9	Fig. 16, Fig. 17 Fig. 18
1	240	110/240	240	150*110/240	1, 0.95, 0.9	Fig. 19, Fig. 20 Fig. 21

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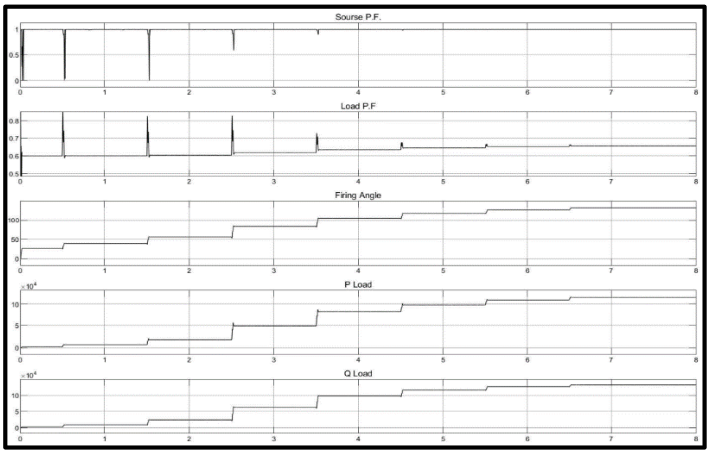

Figure 13: ANN PFC, 240V, Desired PF=1

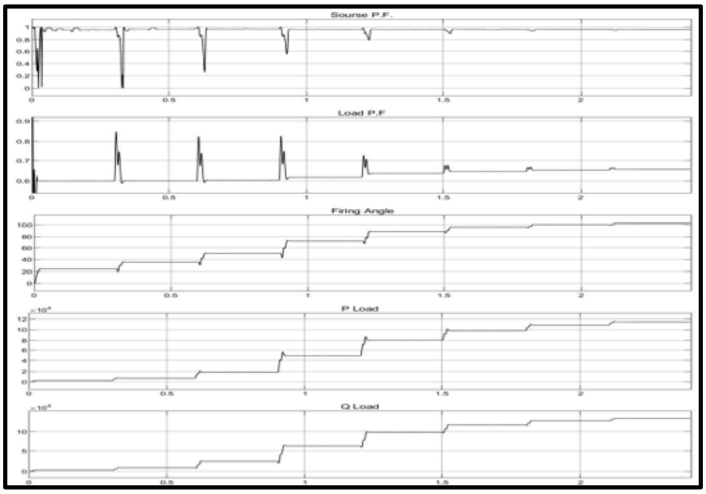

Figure 14: ANN PFC, 240V, Desired PF=0.95

Figure 15: ANN PFC, 240V, Desired PF=0.90

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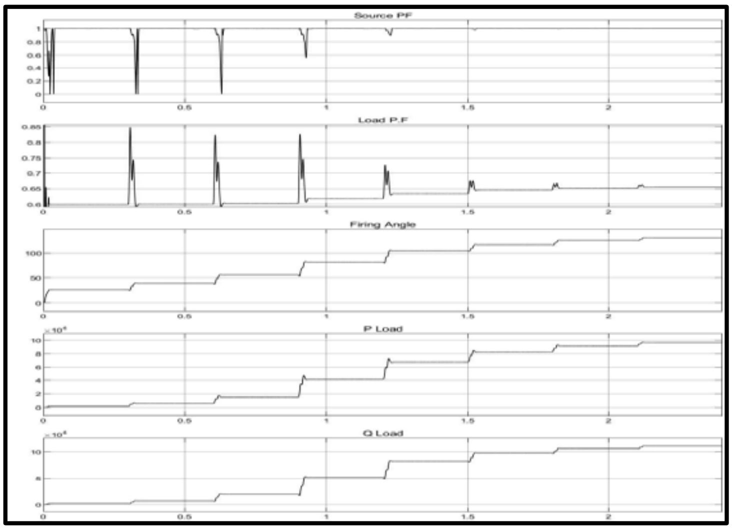

Figure 16: ANN PFC, 220V, Desired PF=1

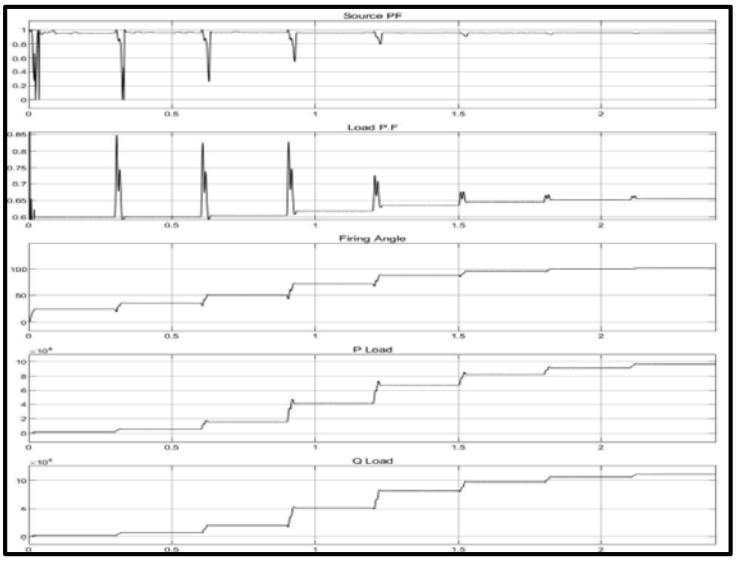

Figure 17: ANN PFC, 220V, Desired PF=0.95

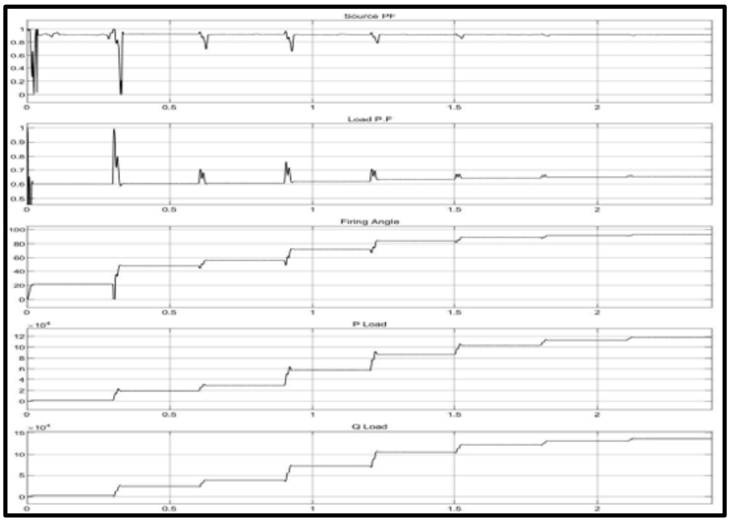

Figure 18: ANN PFC, 220V, Desired PF=0.90

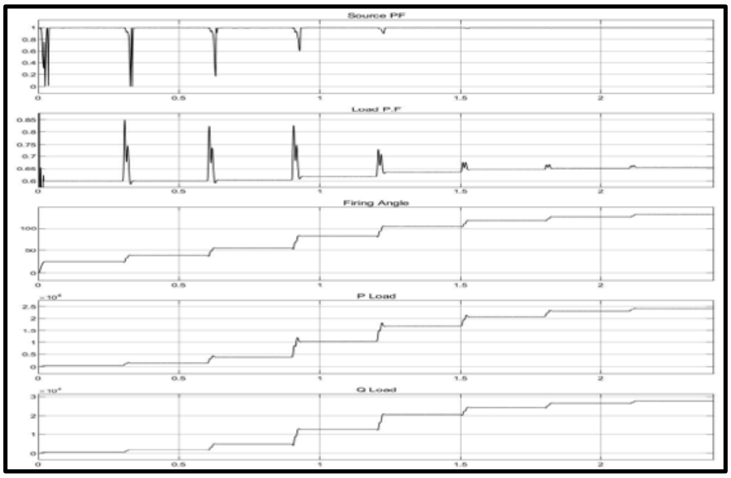

Figure 19: ANN PFC, 110V, Desired PF=1

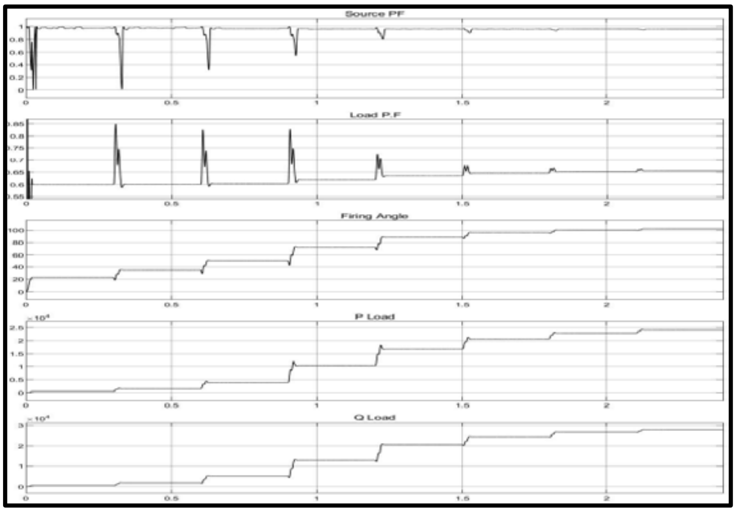

Figure 20: ANN PFC, 110V, Desired PF=0.95

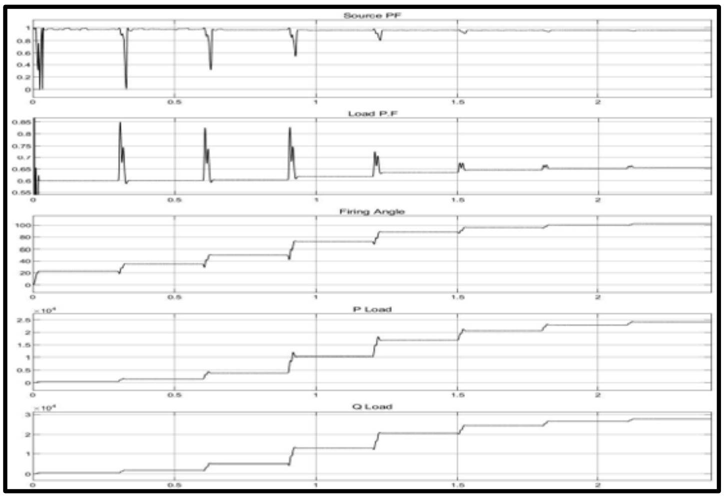

Figure 21: ANN PFC, 110V, Desired PF=0.90

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The results of Group 1 test cases show the successful performance for the ANN PFC to adjust precisely the source power factor to the preset values. The response of the controller takes short time of approximately 40-ms with very acceptable damping behavior. In the second group, in order to fit the result of the trained ANN to the new source voltage levels, each new voltage is used as base voltage for SVC and for ANN input, and the ANN PF is used, as it is, Table 3 lists the test cases for the second Groups.

Table 3: Group 2 test cases

Group No.	Base Voltage (Volt)	Source Voltage (PU)	SVC Base voltage (Volt)	SVC Rating (kVAR)	Desired Power Factor	Results Figure
2	415	1	415	150	1, 0.95, 0.9	Fig.22, Fig.23 Fig. 24
2	230	1	230	150	1, 0.95, 0.9	Fig. 25, Fig.26 Fig.27
2	120	1	120	150	1, 0.95, 0.9	Fig. 28, Fig. 29, Fig,30

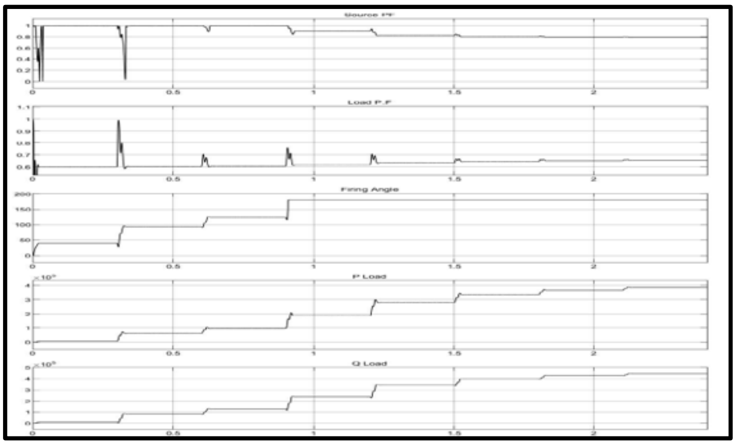

Figure 22: ANN PFC, 415V, Desired PF=1

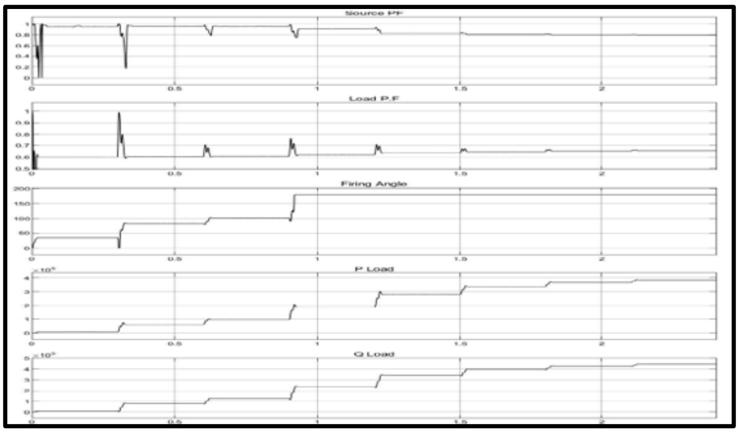

Figure 23: ANN PFC, 415V, Desired PF=0.95

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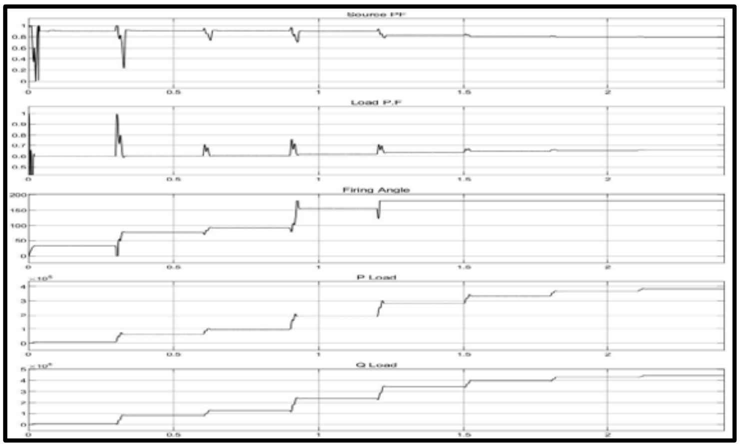

Figure 24: ANN PFC, 415V, Desired PF=0.9

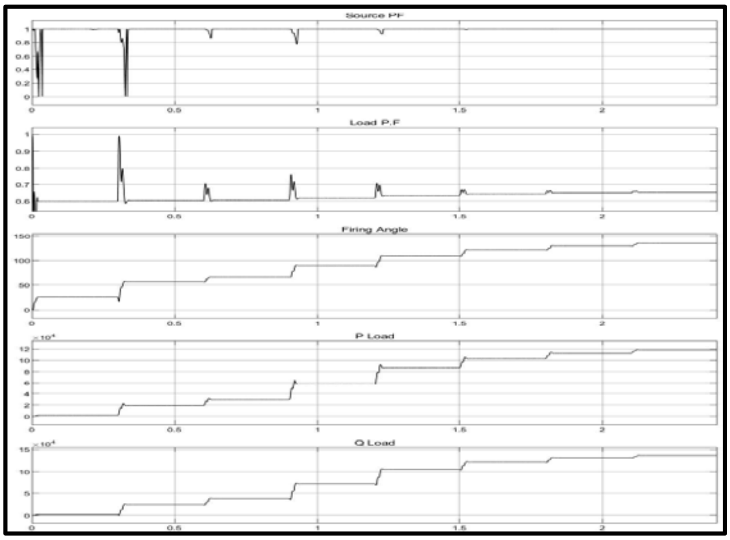

Figure 25: ANN PFC, 230V, Desired PF=1

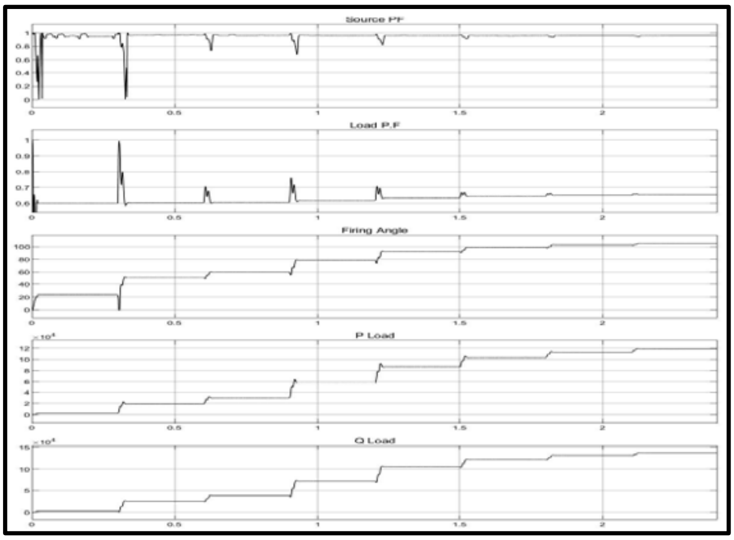

Figure 26: ANN PFC, 415V, Desired PF=0.95

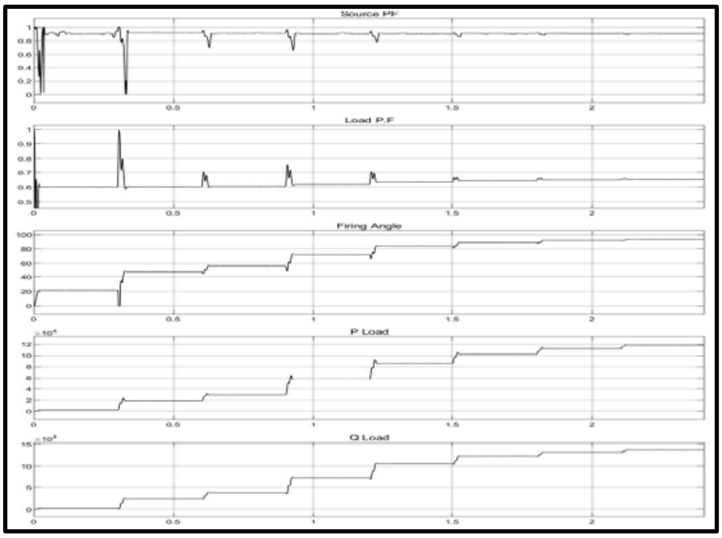

Figure 27: ANN PFC, 230V, Desired PF=0.90

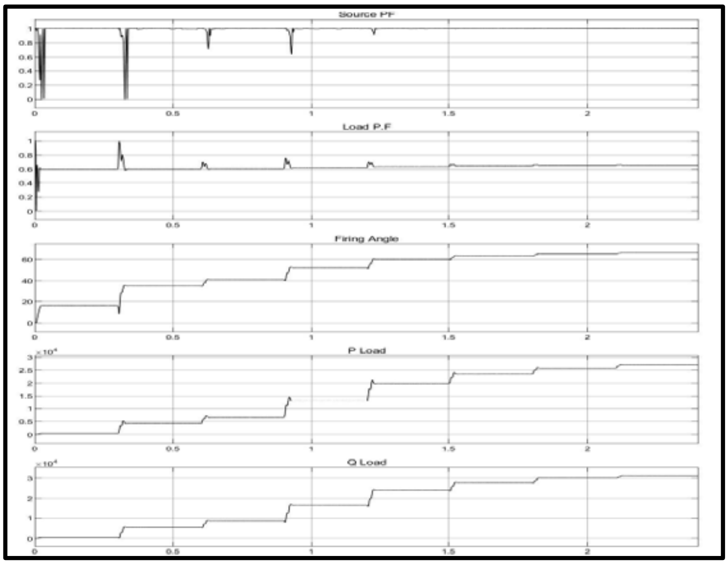

Figure 28: ANN PFC, 120V, Desired PF=1

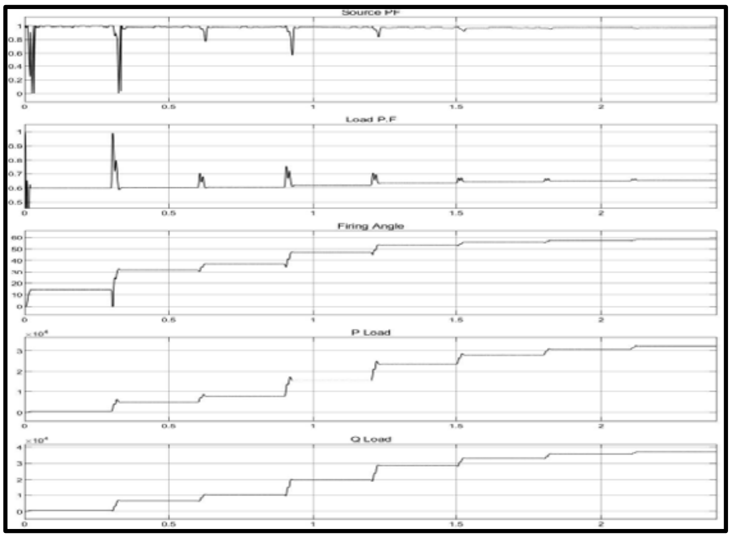

Figure 29: ANN PFC, 120V, Desired PF=0.95

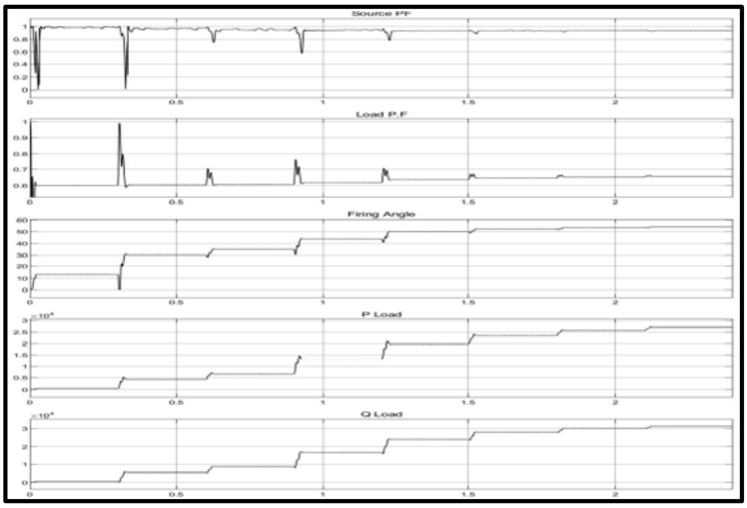

Figure 30: ANN PFC, 120V, Desired PF=0.90

The test cases for Group 2 show that the ANN PFC function can be extended to different voltage levels to that are used in the training process, and still its performance is accurate to correct the source power factor to the desired value up to the maximum capacity of the SVC. If the preset power factor requires higher reactive power beyond SVC capacity, the ANN PFC set the thyristor firing angle to maximum in order to deliver to the system maximum available reactive power from the SCV capacitor. Figure 21 and Figure 22 present clearly this case when the required reactive power is higher than the SVC capability.

6. Conclusion

The article started with comprehensive survey to discuss the different direction in technology to design PFC controllers. Then the paper investigated two new different approaches to design ANN PFC controller that tunes SVC to correct the source power factor of single phase circuit.

The first approach trains a simple ANN (SANNA) using two input signals; nominal voltages (V_n) for three different voltage levels, and the related reactive power values (Q_{SVC}) generated from SVC at different firing angle values. The output signal from the ANN controller is the firing angle (Target). The second approach has used cascaded ANN (CANNA) with same input signal as SANNA. In this approach an intermediate ANN is used to predict the SVC reactor voltage, which is utilized as third input to the main ANN to determine the required firing angle. The training regression and performance and as well as the calculated error for both approaches showed that CANNA is better than SANNA.

Then, CANNA PFC was used in single phase circuit with variable load at low power factor (approximately 0.6). Nine 9 test case were carried out to confirm that the ANN controller performs accurately.

To use the same controller with its trained algorithm as general PFC controller for different voltage levels not included in the ANN training process, the SVC component were resized to fit the base ANN controller (150kV at 240 Volt). This was done by considering the new voltage is the base voltage. Another 9 test cases were carried out using the same single phase circuit to validate the operation of the ANN PFC controller when it is used in extend range for voltage levels.

From the 18 test case that were carried out with differ voltages levels and different loading scenarios, the results show that ANN PFC controller performance is accurate and fast even with the extended voltage range.

For future work, the same CANNA may be used as reactive power compensator to stabilize the network voltage profile.

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