AUTOMATIC LOAD BALANCING FOR DISTRIBUTION TRANSFORMERS

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Degree of Master of Science in Electrical Engineering

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Dissertation submitted in partial fulfillment of the requirements for the
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DECLARATION

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Prof. J.P.Karunadasa

ABSTRACT

Automatic load balancer is power electronic based equipment that balances the unbalanced current in the distribution transformers. This is achieved by employing an AC /DC/AC bidirectional current controlling system. The basic principle of this equipment is to draw currents from lightly loaded phases and inject it to heavily loaded phases in such a way that the currents in three phases at the transformer are balanced.

The Automatic Load Balancer proposed in this research consists of a main controller and a bidirectional-inverter. The main controller monitors the current in each phase and computes the unbalanced current that should be injected to or drawn out from individual phases. The computed currents are then injected or delivered as appropriate through the bidirectional-inverter using current control PWM. Therefore, any unbalance in current caused by the loads is rapidly and successfully corrected to ensure balanced three-phase currents at the transformer output, all the time.

Performance of the load-balancer was tested under both the steady-state and dynamic unbalanced current conditions. The results showed excellent performance under both conditions. Thus, the developed load-balancer is a sustainable and advanced solution for the rough manual load-balancing done at present.

ACKNOWLEDGEMENT

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LIST OF ABBREVIATION

PWM	Pulse Width Modulation
HB	Hysteresis Band
RMS	Root mean Square
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
HBCC	Hysteresis Band Current Controller
PLL	Phase Locked Loop
A/D	Analogue to Digital
DAC	Digital to Analogue Converter

OBJECTIVES

The main objective of this research is to develop a power electronic based solution for automatic load balancing for a distribution transformer, and thereby to minimize distribution losses, preserving economic viability.

1 INTRODUCTION

The electricity network of Sri Lanka has been expanded all over the country within the last few years by providing electricity to all. Minimizing the electricity losses, improving power reliability, quality and, providing electricity safety are main challenges for electricity providers. According to the present statistics, it has been identified that the electricity losses are being reduced by the improvements of the network, loss reduction activities and projects. Electricity losses can be discussed under three categories which are generation, transmission and distribution losses. However considerable amount of electricity losses belongs to the distribution sector. Electricity losses of Sri Lanka are shown in Table 1.

Table 1: Electricity Losses in Sri Lanka

Year	2014	2015	2016	2017	2018
Transmission and distribution losses(On net Generation)	10.47%	9.96%	9.63%	8.45%	8.34%

The cost of electricity network losses is a considerable amount when it is compared with the national economy. One percent (1%) saving is equal to millions of rupees and it directly affects the foreign exchange which can be considered as the main reason for minimizing the electricity losses. However, there are some practical and economic limitations when minimizing the electricity losses. A considerable amount of electricity losses belongs to the distribution sector and economically viable solutions are required to minimize such losses. Distribution losses are discussed under two main categories such as technical and non-technical losses. Unbalanced losses, I^2R losses, current harmonics are identified as major components under technical losses.

Distribution transformer is one of the major components in the distribution network, and it is costly equipment in the distribution network. The proper maintenance of equipment, minimizing of electrical losses, and effective utilization of equipment can be identified as major aspects for minimizing electrical and economical losses in the distribution network. From a few of identified case studies, it has been noticed that the effect from economic losses are higher than technical losses.

1.1 Electricity Losses

Electrical power is transmitted from larger generation plants to consumers through the larger electricity network. Long transmission lines, distribution lines, and equipment create power losses and a considerable portion of energy losses is due to the Joule effect. The energy is lost as heat in the equipment and conductors in the distribution and transmission networks.

Typical power losses in main sections of generation, transmission and distribution networks are shown below.

- Generator to transmission network 1-2%
- In transmission line 1-3%
- Transmission lines to Distribution network 1-2%
- Distribution transformers and feeders up to consumer 4-8%

The total losses from the generation plant to consumers are in the range of 8-15% and it is depending on the technologies and the expansion of the network.

1.2 Distribution Losses

A considerable amount of entire electricity system losses belongs to the distribution sector, which is around 50% to 80% of the total electricity losses.

The larger amounts of these losses occur in primary and secondary distribution lines in the form of technical losses and non-technical losses.

Conductors in distribution lines and equipment dissipate energy while in operation, and these losses are technical losses. The amount of losses depends on characteristics of network and the operation of networks. Variable technical losses and fixed technical losses are categories of technical losses.

Variable losses are created due to resistance of conductors and resistances of contact points. It is proportional to the square of current flowing through the conductors.

Fixed losses include noise losses, leakage current losses, corona losses, dielectric losses and open circuit losses. Fixed losses do not depend on the amount of load current.

1.3 Transformer Losses

Copper losses, iron losses, hysteresis losses, eddy current losses, dielectric losses and stray losses are the main types of losses in e transformers. Hysteresis loss occurs due to asymmetry between rising and falling magnetizations in the core. Copper losses occur due to resistance in the transformer windings. Details of the above losses are given in Figure 1.

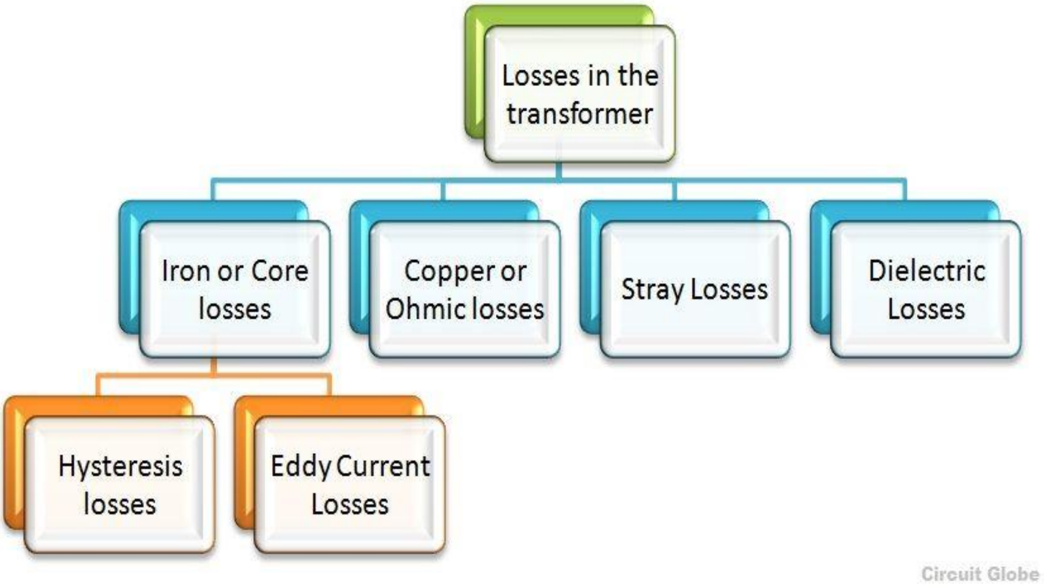

Figure 1: Transformer Losses

1.3.1 Iron Losses

Iron loss can be divided into two parts, hysteresis losses and eddy current losses.

Hysteresis Loss:

Magnetizing force on the core alternates with AC current flowing in the winding. Due to asymmetric magnetic friction of the core for rising and falling magnetizing forces, the magnetization characteristic generates a hysteresis loop on each cycle. Hysteresis loss is the energy spent on overcoming these magnetic frictions and its value per cycle is proportional to the area of the hysteresis loop. Mathematically, hysteresis loss is modeled as,

$$P_h = K_h {B_{max}}^{1.6} f V \text{ Watts}$$

K_h is a constant of proportionality that depends on the quality of the material, f is the frequency of current, B_{max} is the peak value of flux density in the core, and V is the volume of the core.

Eddy Current Loss:

Eddy current loss occurs due to the induced current in the transformer core due to time varying magnetic flux flowing through the core. These induced currents flow over the surfaces perpendicular to the direction of flux. Eddy current loss is minimized by adopting laminated core-structure that inserts breaks in the path of eddy current and selecting core iron having high resistivity. Mathematically, eddy current loss is modeled as,

$P_e = K_e {B_{max}}^2 f^2 t^2 V$ Watts

K_e is a constant of proportionality that depends on the quality of the material, f is the frequency of current, B_{max} is the peak value of flux density in the core, t is thickness of lamination and V is the volume of the core.

1.3.2 Copper Loss or Ohmic Loss

Copper losses are modeled as,

$P_c = \left({I_1}^2 R_1 + {I_2}^2 R_2\right)$

I_1 is primary current, I_2 is secondary current, R_1 is primary winding-resistance, and R_2 is secondary winding-resistance.

Copper loss varies with the square of load current and this is a variable loss.

1.4 Unbalanced Losses

Unbalanced current is a major cause for elevated losses in the distribution system Unbalance current increases transformer copper losses and feeder losses. Besides losses, unbalanced current affects power quality and the stability of the system.

1.4.1 Copper Loss on Unbalanced Current

Let,

$(P_{cu})_{Unbal}$ = Copper loss with unbalanced current

$(P_{cu})_{Bal}$ = Copper loss with balanced current

I_A, I_B & I_C = RMS current in phases A, B and C respectively

R = Resistance per phase of the transformer

Then,

$$(P_{cu})_{Unbal} = (I_A{}^2 + I_B{}^2 + I_C{}^2)R \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots .. (4.1)$$

$$(P_{cu})_{Bal} = 3\left(\frac{I_A + I_B + I_C}{3}\right)^2 R \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots . (4.2)$$

$$(P_{cu})_{Unbal} - (P_{cu})_{Bal} = (I_A{}^2 + I_B{}^2 + I_C{}^2)R - 3\left(\frac{I_A + I_B + I_C}{3}\right)^2 R$$

$$= \frac{1}{3}[(I_A - I_B)^2 + (I_B - I_C)^2 + (I_A - I_C)^2]R \dots\dots (4.3)$$

Right-hand side of equation (4.3) is always positive, which indicates that $(P_{cu})_{Unbal}$ is always greater than $(P_{cu})_{Bal}$, if not equal.

1.5 Shortcoming of Unbalanced Transformer Current

Due to unbalanced transformer current, distribution engineer is faced with various difficulties and power quality issues.

- Increased copper losses in the transformer
- Increased neutral current
- Increased noise and vibration of the transformer
- Decrease the life span of the transformer
- Underutilization of investment
- Cost of manual load balancing
- Excessive heating due to flow of negative sequence currents
- Difficulties due to transformer overloading

Main reasons for current unbalances are,

- Change of consumer patterns and heavily loaded equipment

- Changing of consumption in peak, day and off peak
- Solar PV connections and their variations of generation
- Change of weather and climate

1.6 Present Load Balancing Procedure in Sri Lanka

Manual load balancing is the method currently used for load balancing in the distribution transformer in Sri Lanka. This is done usually as a routing job once a year or in random field inspections. After identifying major unbalanced conditions, the behavior of the load profile has to be identified by using load reading at peak and off peak time period. The load profile and the behavior of major loads are analyzed with the collected data. After that, the single phase loads which are more similar to load pattern and connected to heavily loaded phases are identified. After that these identified single phase loads are transferred to lightly loaded phases balance the three phases. To find transformer load profile and single phase loads, the service of a field expert is needed and the success rate of load balancing depends on his experience and knowledge. Sometimes it is required to complete few load balancing cycles to achieve the desired result. This trial and error method is not an efficient method. Further, to identify the load pattern and to rearrange single phase loads, a few days of labor, supervision, materials and overhead are needed.

1.7 Practical Difficulties of Manual Load Balancing

Manual load balancing is a trial and error method. The success rate and the efficiency of this method is very low and it depends on the experience and the knowledge of the field expert. It requires considerable number of working days and considerable labor hours to implement. From this method, it is not possible to mitigate the issue as expected. It is also not a sustainable solution to minimize the distribution losses because it may be applied on peak time period which doesn’t give solution for the changes of load profile in other periods. Changes of consumer patterns, use of heavy load equipment's, consumption changes in peak, day and off peaks, Solar PV connection and their variation of generation and weather and climate changes are major reasons to change the load pattern. Due to the above reasons, manual load balancing is not a sustainable solution for the load balancing.

1.8 Methodology

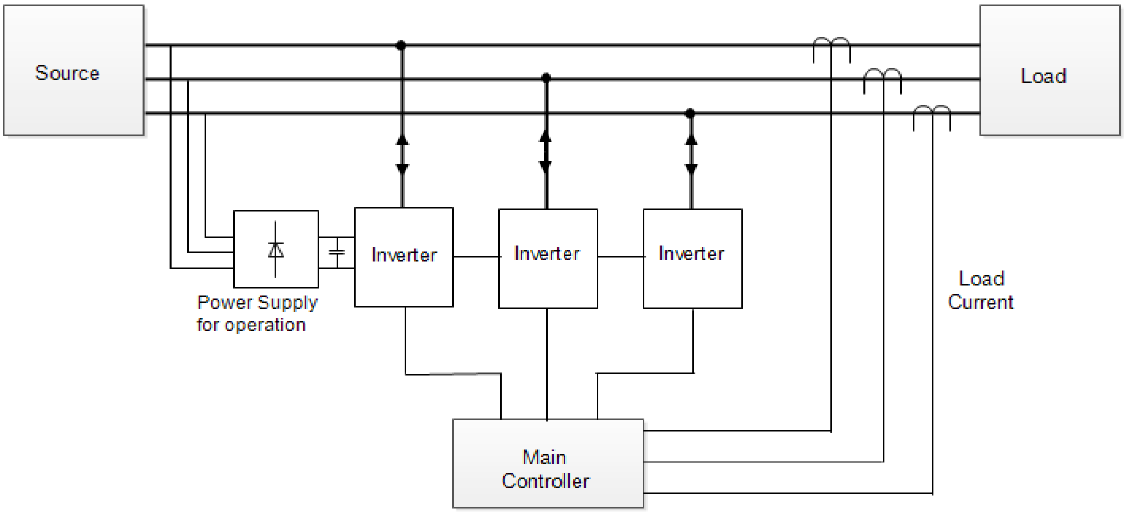

Figure 2: Schematic Diagram of Automatic Load Balancer

The proposed system draws current from lower current phases and injects it to high current phases using AC/DC/AC current control inverters. Switching pattern is dynamically changed to maintain balanced current in three phases.

RMS values of load current in the three phases are measured using current sensors and the profiles of current waveforms are extracted using PLL (phase locked loop) sensors. Increase or decrease of current in a given phase is done inphase with the load current but the RMS values of currents are brought to an equal level in the three phases at the PCC (point of common coupling). The controller determines the amount of current to be extracted from or injected to individual phases and accordingly generates current reference signals for the hysteresis current controllers.

Hysteresis band current controllers generate switching signals for each inverter, which are delivered through gate drivers.

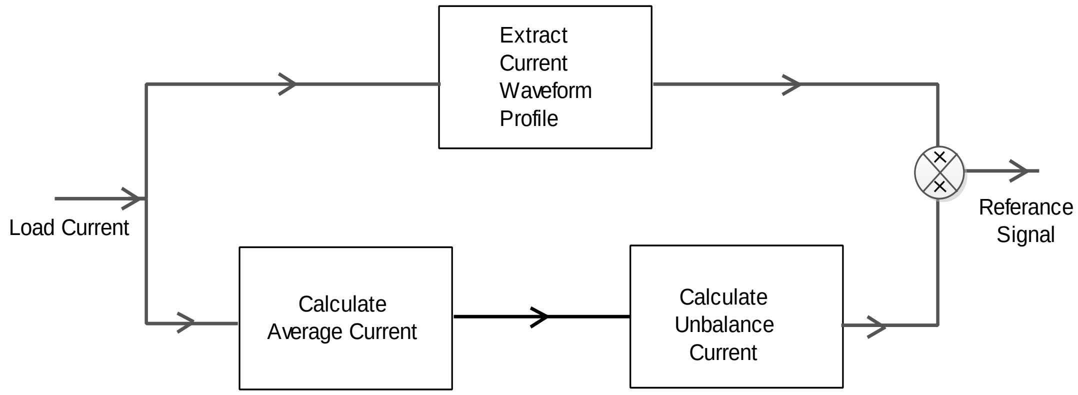

Figure 3: Process of Generating Reference Signal

1.9 Typical Arrangement of Distribution Transformer

Majority of distribution transformers of Sri Lanka electricity network consist of 100kVA, 160kVA and 250kVA capacities and the feeder arrangement also differ with each other with the requirement of feeding area and the terrain. $70mm^2$ All Alloy Conductors (AAC) and Aerial Bundle Conductors (ABC) are widely used for the low voltage distribution and the rated current of that is 160A. HRC fuse of 160A and 125A are installed at the front of the feeder as the protection device for the distribution feeder. In most of the cases it is noticed that more feeders are connected to the transformer than in typical arrangements. The common coupling point is LT flag of the transformer bushing. The detail of typical transformer arrangement is shown in Figure 4.

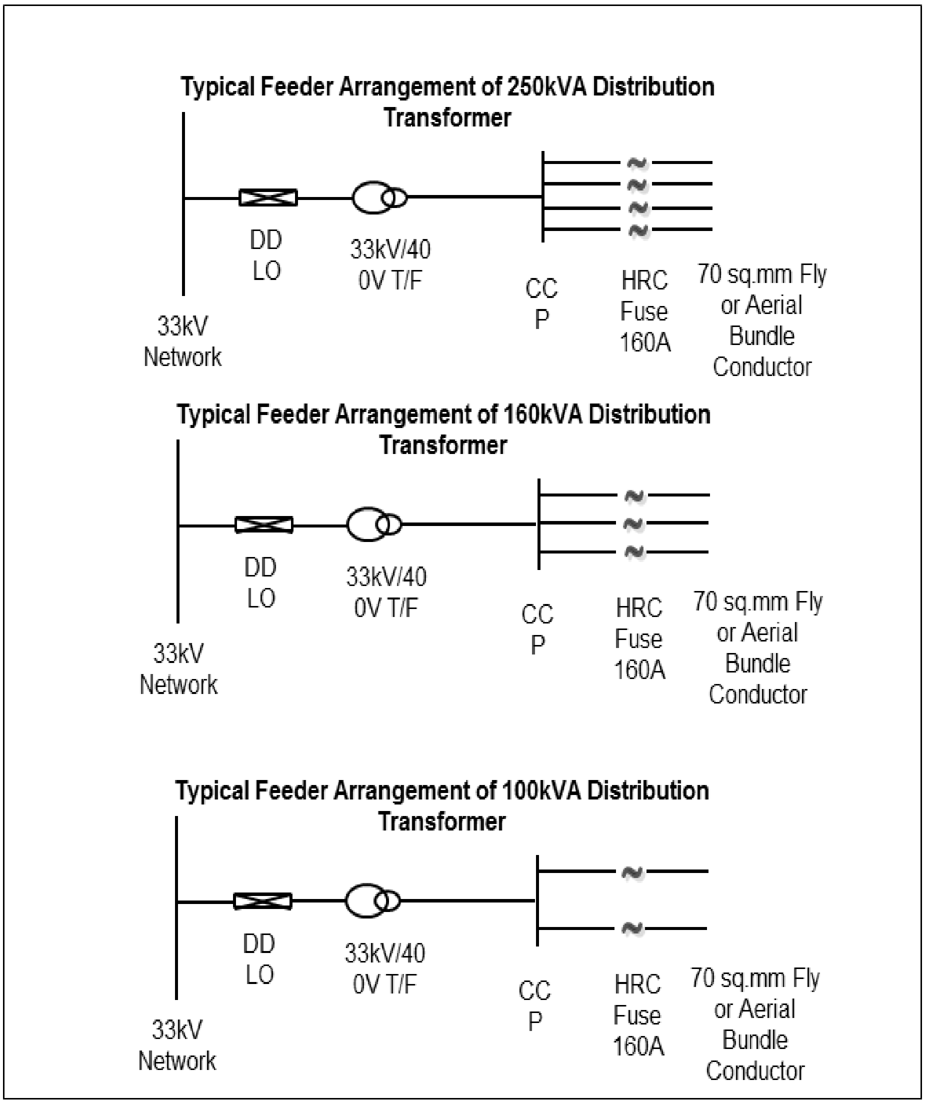

Figure 4: Typical Distribution Substation Arrangement

Load reading of 5 nos. of distribution transformers were collected in consecutive 3 days which were 22nd , 23rd and 24th July 2018 in Panninpitiya feeder 7 by 15 minutes' intervals. Above days were selected with the intention of selecting a day in the week end (Sunday) , first day and second day of the week to identify proper load variation pattern. Sections 5.1.1 to 5.1.5 describe load variations of the selected distribution substations which are named as p007, P078, P084, P012 and P170.

1.9.1 P007

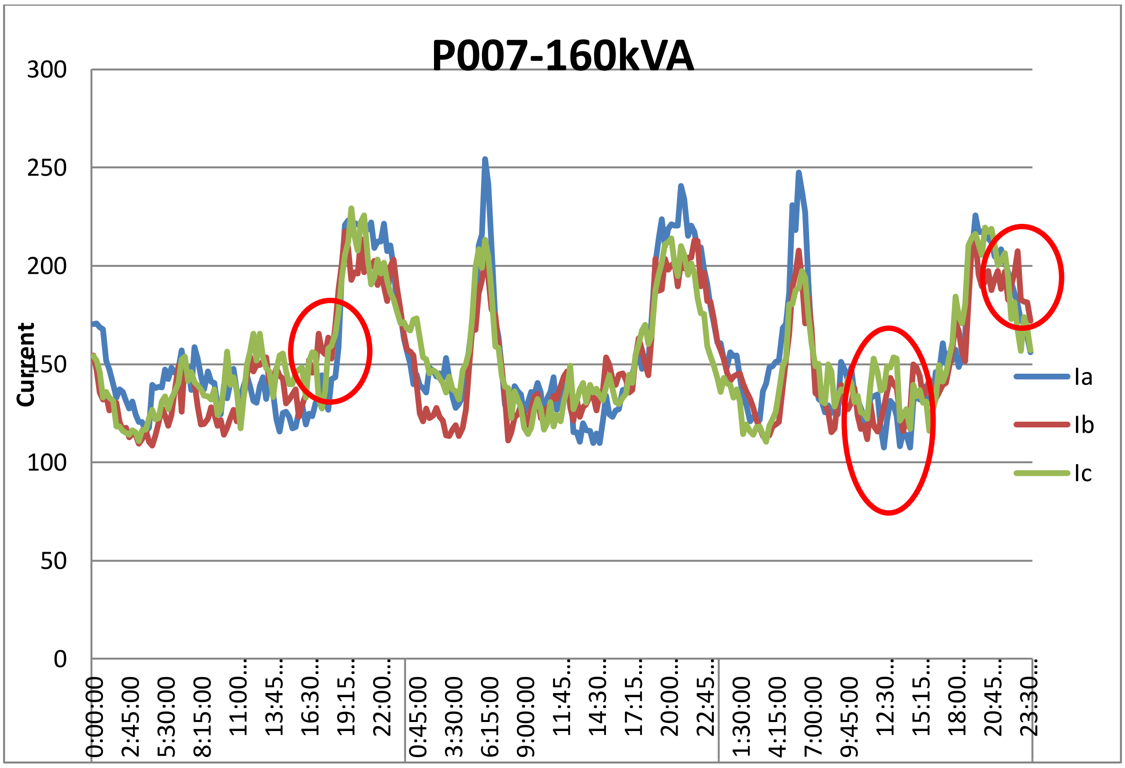

Figure 5: Load Profile of P007

According to the load pattern of 22nd July (Sunday) there was no morning peak that the other two days (Monday and Tuesday) had. Mostly loaded phase was changed within couple of minutes and the pattern randomly continued for few hours. The loading pattern of night peak of above three days had considerable difference in loading shape and changes of maximum peak. When analyzed the day time of above three days, it had considerable deviations and the instantaneous maximum current of loading was changing in small intervals.

1.9.2 P078

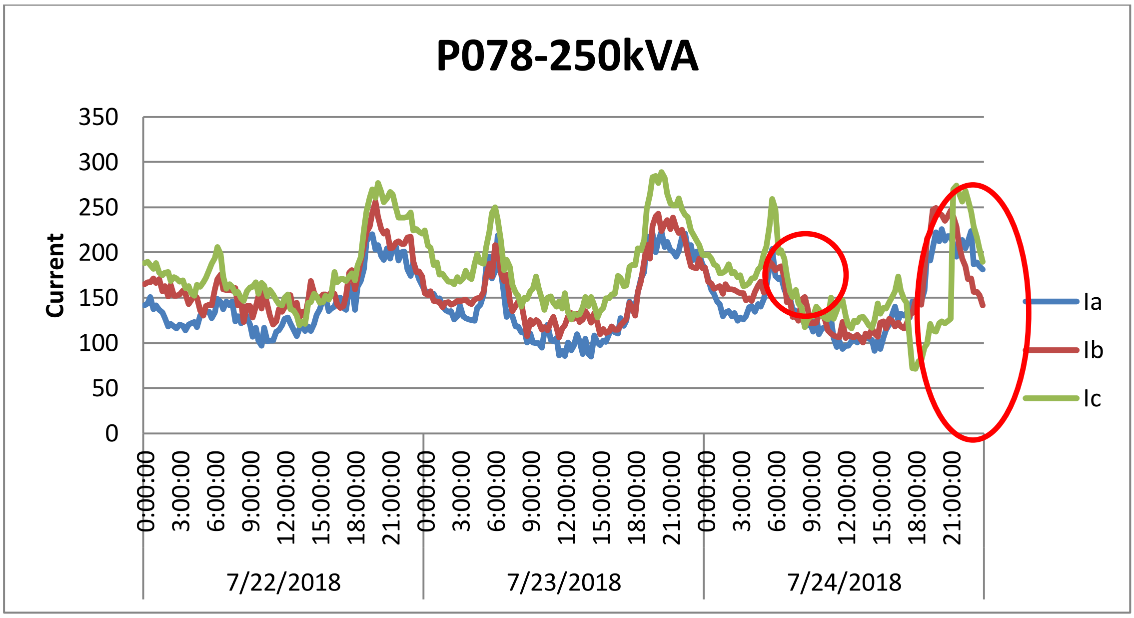

Figure 6: Load Profile of P078

Instantaneous maximum phase current was changing in various time periods during above three days. Sudden variation, changing of maximum phase current and the difference of loading on weekends and week days were clearly noticed in the above figures. This load profile clearly indicates the randomness present in the distribution load.

1.9.3 P084

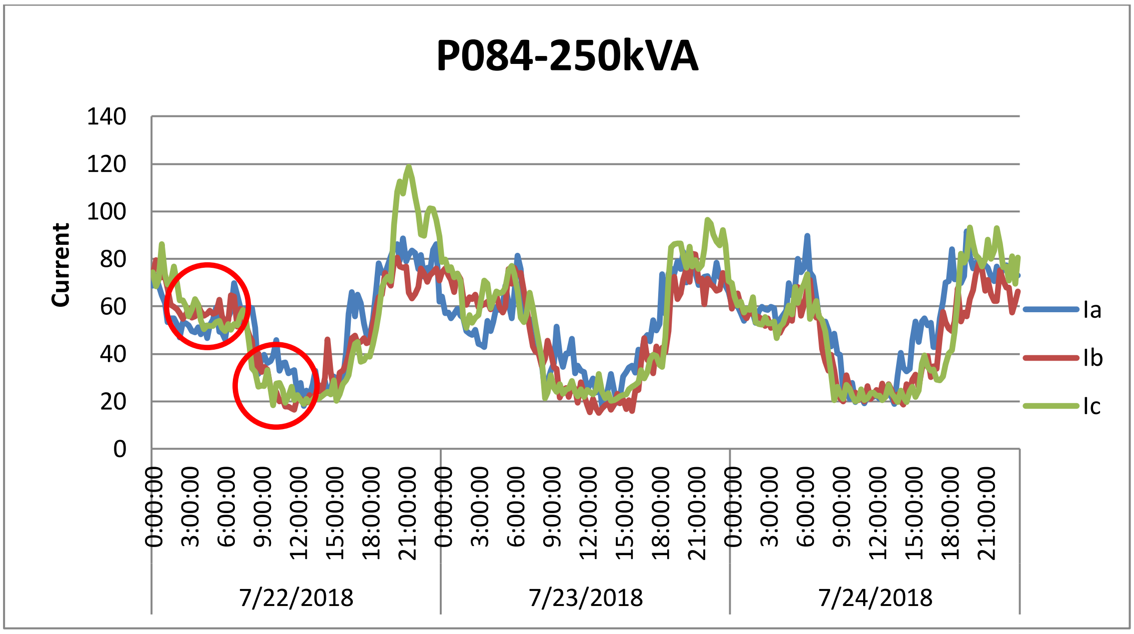

Figure 7: Load Profile of P084

Phase C of P084 load profile indicated the variation of maximum current to minimum current during few hours. Behaviors of peak and off peak loads are completely differing among the selected days. Prediction or identifying of maximum current phase or minimum current phase becomes very difficult.

1.9.4 P012

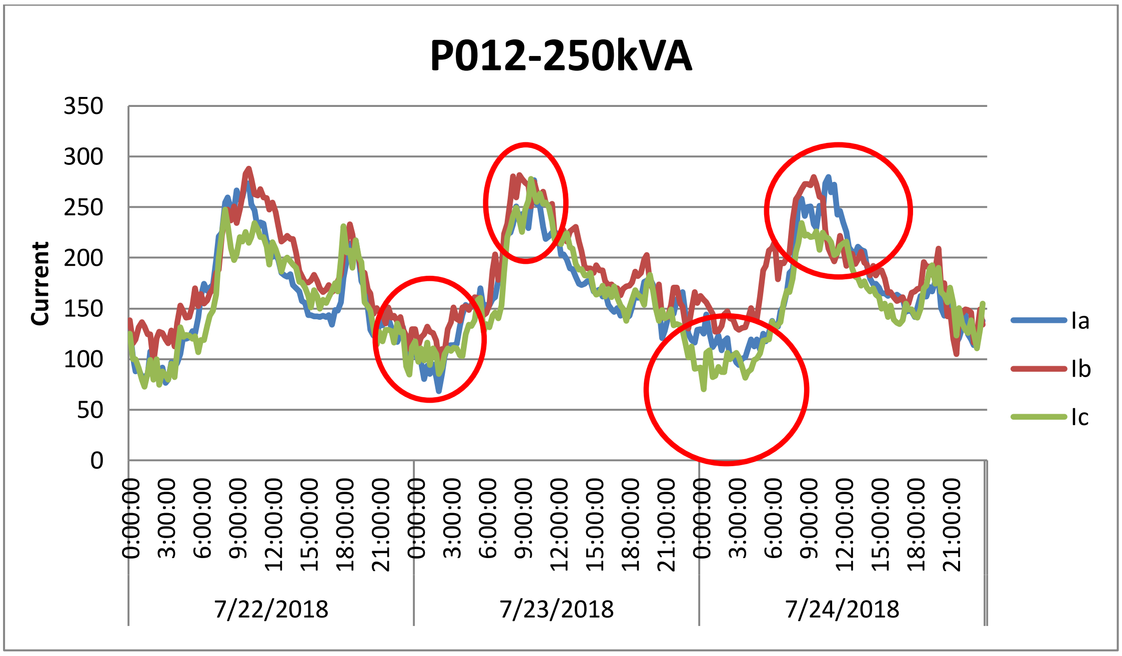

Figure 8: Load Profile of P012

The specialty of this load profile is that there is no night peak and it has only day peak as sharp edge. The day peak of above three days shows a huge randomness and variation among three phases.

1.9.5 P170

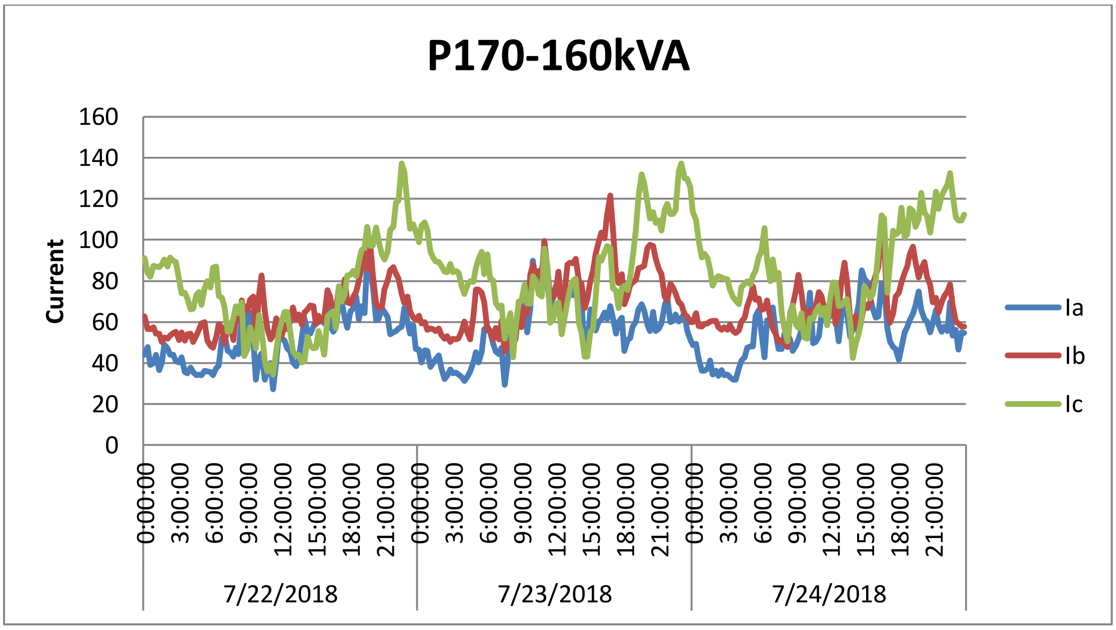

Figure 9: Load Profile of P170

In P170 substation consist with massive variations and randomness in load pattern. Phase- A is having fairly a flat load pattern but phase C is having huge variations. Phase B is having average variations with respect to phases A and C.

Typically, these types of loads are very difficult to balance by manual load balancing.

1.10 Summary of Identified Substation

Table 2: Summery of Load Profile

Sin No	Capacity kVA	No of consumers	Feeder length Km	Maximum Load kVA	Minimum Unbalance percentage	Maximum Unbalance Percentage
P007	160	577	10.4	153.34	0.29	16.84
P078	250	726	12.7	167.65	0.94	30.93
P084	250	37	6.1	62.68	0.89	50.4
P012	250	615	11.2	185.61	0.81	37.74
P170	160	69	4.7	68.71	0.51	59.74

Summary of identified figures of distribution substation are tabulated in Table 2. P007, P078 and P012 loaded more than 70% from rated capacity. Maximum current unbalance is near 60 % and average current unbalance, around 30 %.

2 LITERATURE REVIEW

Load balancing can be considered as the main option discussed under the lost reduction in distribution networks. Many researches have been conducted for reducing current unbalances. Few of these are briefed below with their technical specifications.

2.1 LV Self Balancing Distribution Network Reconfiguration for Minimum Losses by D.V. Nicolae, M.W. Siti and A.A. Jimoh

This paper refers to two types of switching for primary distribution systems, namely normally close switch which connects line sections, and normally open switch (on the tie line) which connects other two lines. For balancing, normally closed switch is opened and normally opened switch is closed (at zero crossing point). With the use of artificial intelligence, telecommunication and power electronics, the phase balancing problem is solved automatically.

This method uses neural networks to turn on/off different switches in balancing process. Switching ensures that each load is connected only one phase at a time. For each loading condition, the neural network is trained for the minimum loss configuration. The neural network directly communicates with switch selector.

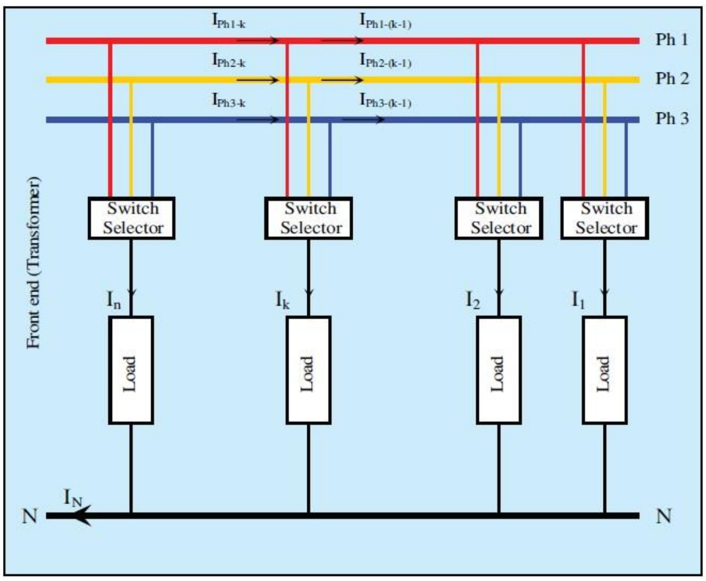

Figure 10: Switch Selector

The task of switch controller is the switching between phases as determine by switch selector. This is designed to switch at zero crossing of current to minimize the switching transients on the loads. The switching from one phase to another is completed within a maximum duration of 17 ms, and as this is very short deep that does not affect any appliance in the household.

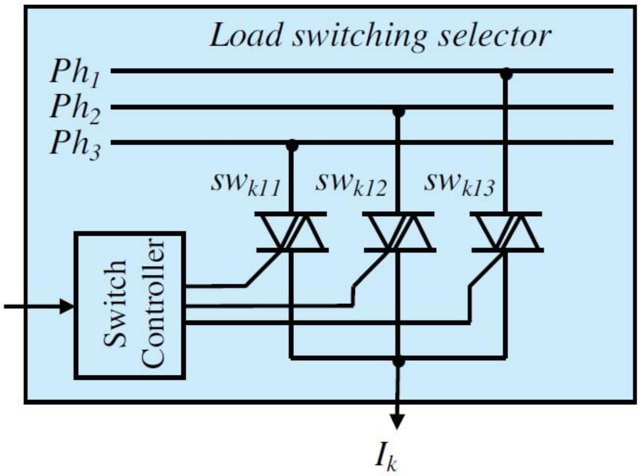

Figure 11: Switch Controller

This technique is recommended for few loads in distribution feeders and not suitable for large networks having considerable amount of loads.

2.2 Single Phase Load Balancing in a Three Phase System at Distribution and Unit Level by Michella Fahim, Moustapha EI Hassan and Maged B. EI Najjar

This paper points out that the highest rate of unbalancing is witnessed at the low voltage distribution level, causing the flow of highly distorted current in neutral wire. The paper concentrates on consumer load rearrangement at the installation level of the unit itself. The process is done through the load optimization by moving heavy single-phase loads to the lightly loaded phase through a switching system connected to it. The above method takes the required measurements of each device (current consumption) using metering sensors. Then this data is transmitted via the communication interface in the central computing unit to the balancing algorithm. Once the calculations are done and the set of loads per phase is selected, a transmission link sends signal to the switch selector connected to every load. The load selector switch is formed by three triacs, which switch the connection of the load to the relevant line.

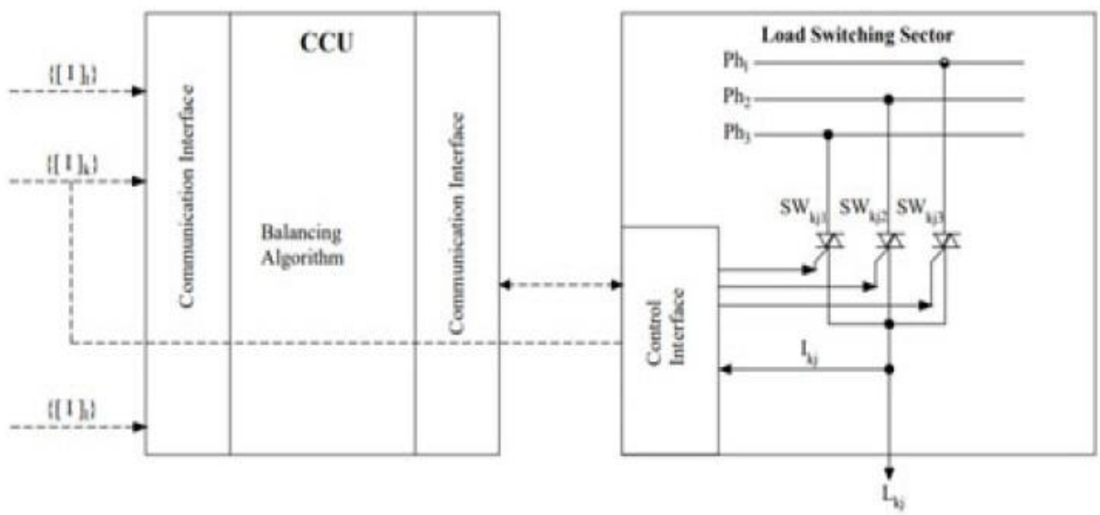

Figure 12: Control Interface

The balancing algorithm used in this paper works independently with network's size which makes it more accurate. The suggested method is based on a single loop load exchange from one branch to another. As the loads are dynamic and their variation are not uniform and cannot be controlled, the measurements of current at each device or load are repeated every 30 minutes. At that time, the current unbalance percentage is calculated. If the unbalance percentage does not surpass the standard, no action is taken and a new set of data is entered in the next 30 minutes. Otherwise, the original unbalanced load connection along with the current values is sent to the algorithm to find the balanced load.

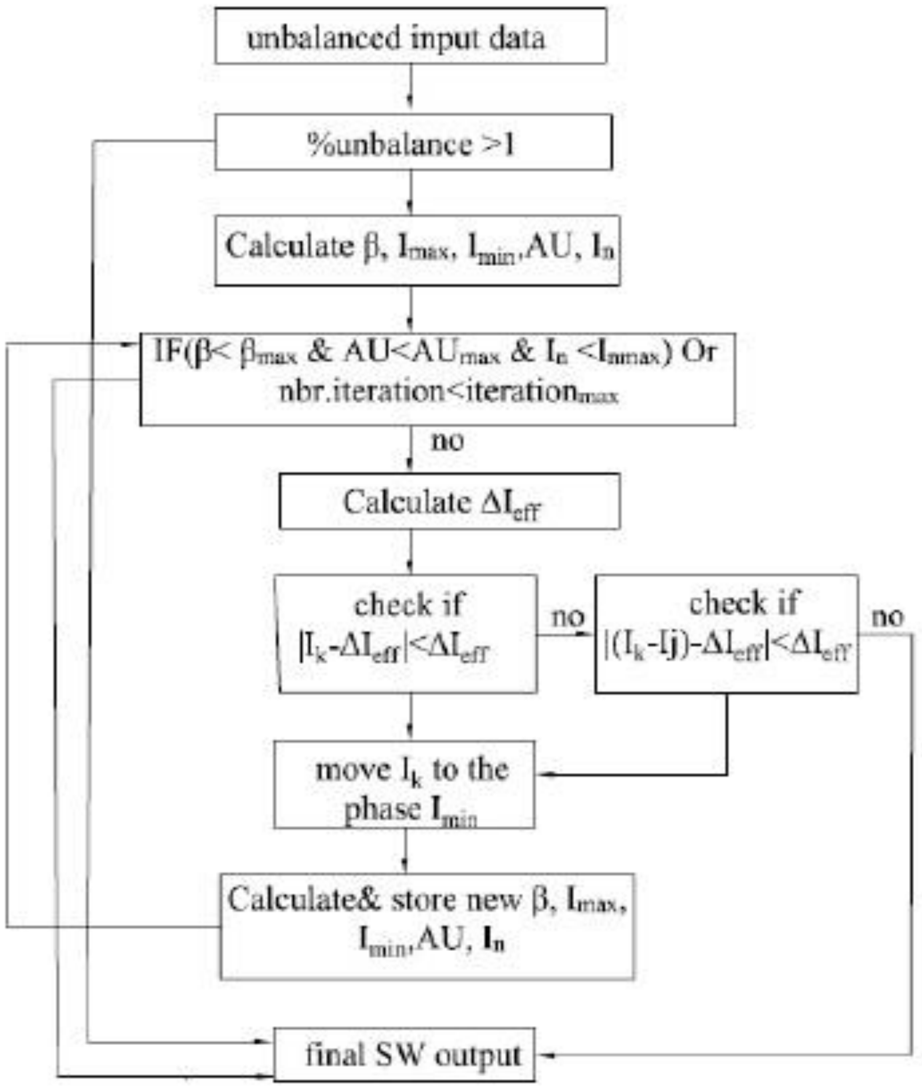

Figure 13: Process Flow Diagram

The output of algorithms is the switching status of the balanced set of loads. The new load arrangement is returned and the status of the switches is modified correspondently. The same process is done on the LV distribution level where single phase loads are transferred from one branch to the feeders with minimal burden. The configuration continues until all constrain are met to reach the balance.

2.3 Smart Electric Grids Three-Phase Automatic Load Balancing Applications using Genetic Algorithms by A. Gouda, A. Abul-Farag, H. Mostafa and Y. Gaber

In this case, the load is balanced unit wise using genetic algorithms. Three single phase contactors are connected to three phases (R, Y and B), as shown in Figure 14 for each single phase load. Every effort has been taken to ensure that only one contactor is closed at a time; otherwise line to line short circuit would occur.

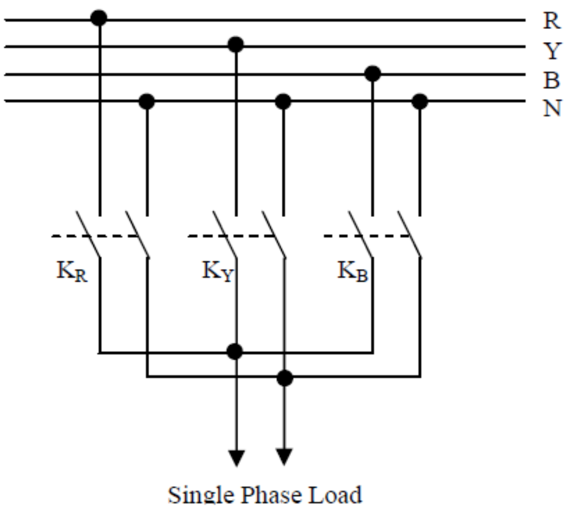

Figure 14: Switching Mechanisum

For each of these loads, a measuring device computes the load current and its corresponding power factor and transmits the results from the slave unit through the communication network bus (using RS-485) to the master unit. Then the data is processed by the central computing device which is connected through the internet to the electricity distribution company. The central PC collects the data from all the loads under its control. It is then responsible for deciding which load is to be connected to which line of the three phases according to the optimizing technique implemented in its software. The decision for each load is then sent back from the master unit to the slave unit at the corresponding load. This system includes a UPS in order to eliminate the switching transient from the load supply during the transition from one phase to the other. The system block diagram is shown in Figure 15.

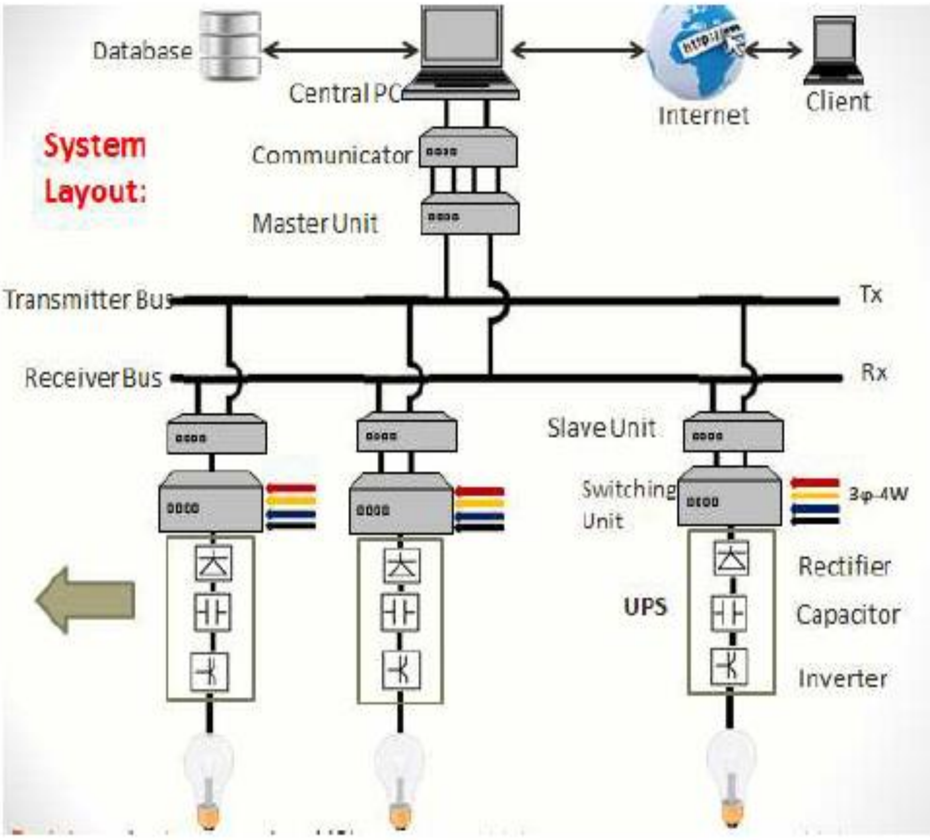

Figure 15: System Process Diagram

3 MODELING OF AUTOMATIC LOAD BALANCER

3.1 Techniques of Current Injection

Current injecting to electricity network and drawing current from electricity network, through proper controlling channel is the main technical task allocated to the proposed Automatic Load Balancer. Bi-directional current controlling mechanisms are introduced for the purpose of the current injections and the current drawings. Hysteresis band Pulse width Modulation is the main technique used for the controlling bi directional currents. The current wave profile of the three phase load currents are captured by using current sensors connected to the load cables. The currents that need to be injected and drawn for balanced three phase loads are modeled by the algorithms in phase with the captured load current profiles.

Hysteresis band PWM is basically an instantaneous feedback current control method where the actual current continually tracks the command current within defined hysteresis band. Hysteresis control schemes are based on a nonlinear feedback loop with two level hysteresis comparators. The switching signals are produced directly when the error exceeds an assigned tolerance band.

The sensitiveness and the accuracy of the current controlling depend on the selected value of the Hysteresis Band (HB). Inverter maximum switching frequency, the rate of change of currents and the voltage ripple at point of common coupling are major factors that decide the value for Hysteresis band. When the width of HB is increased, the switching frequency is decreased but the ripple of current waveform is increased. When the width of HB is decreased, ripple in the current waveform is decreased (smoothness of current wave form improved) but switching frequency is increased. An increase of switching frequencies directly affects thermal losses and the efficiency of the system. Hence optimized value for the hysteresis band is important as a compromise between current waveform quality and efficiency.

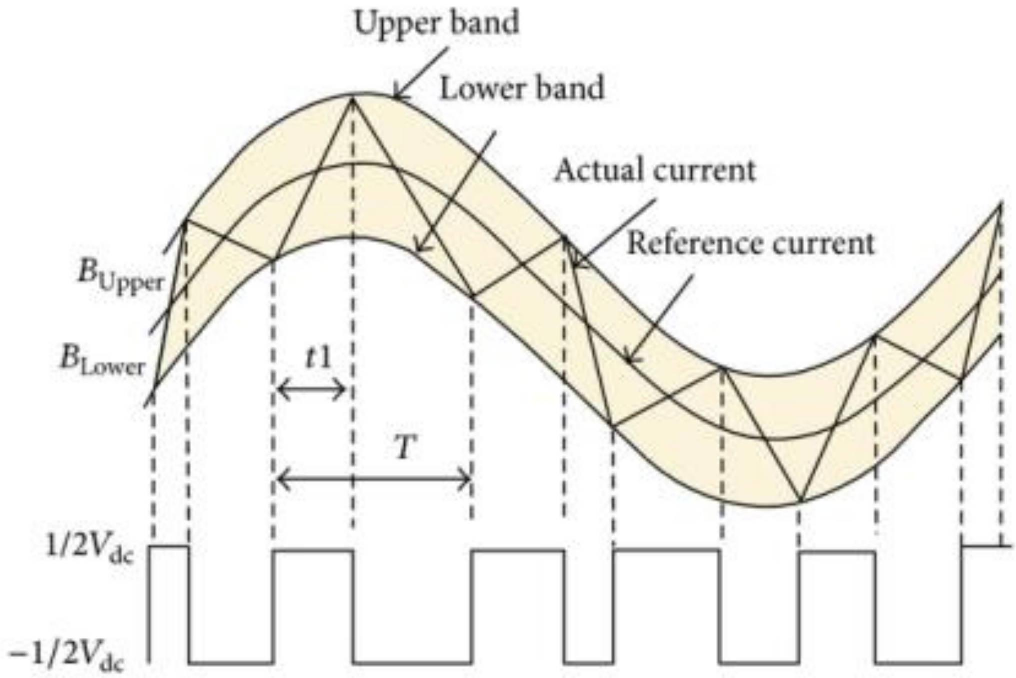

Figure 16: Hysteresis Band PWM Signal

3.2 Design of Inverter

Width of HB, magnitude of required current, switching frequency and the voltage at the output are major factors to be considered for the designing of the inverter. After analyzing all the requirements and field data, the inverter was designed to handle capacity up to 100A per phase. Width of HB and switching frequency are inversely proportional. Width of HB of 4A was decided and the corresponding maximum switching frequency was approximately 4 kHz.

3.3 Design of Reference Signal

Reference signal is an input to the hysteresis band current controller conveying the information on the magnitude and shape of the waveform of current that the inverter should deliver.

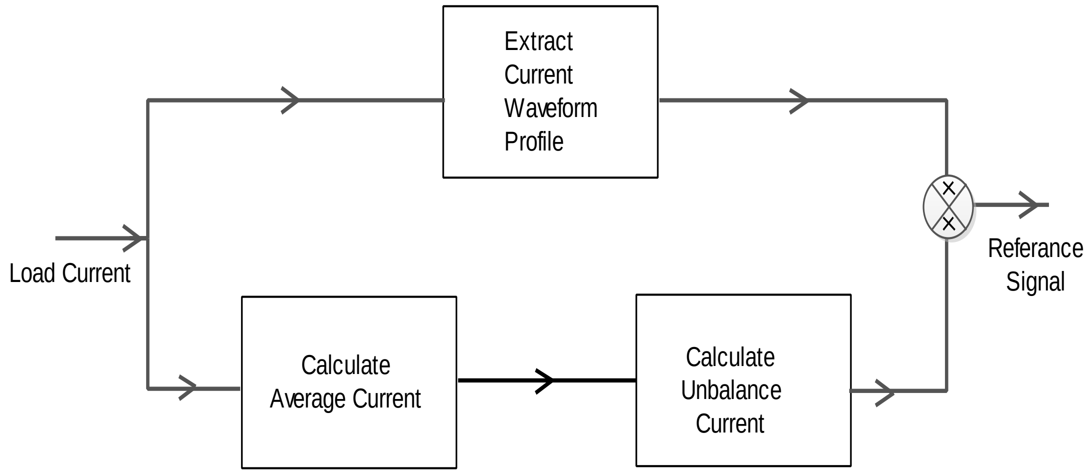

Figure 17: Flow Diagram of Reference Signal

The reference signal for each phase is obtained by multiplying the extracted profile of the current waveform of that phase and the amplitude of current that should be injected to or drawn out from that phase. Unbalanced currents to be injected or drawn are calculated by subtracting individual RMS currents from the average RMS current of three phases. The block diagram of generating reference signals is shown in Figure 17.

3.3.1 Calculate Amplitude of Reference Signal

Three phase load current signals are taken into main controller and respective RMS values of each phase are calculated by using the RMS blocks. Then the average RMS value is computed by adding them together and dividing by 3. Next, the average RMS current is subtracted from the individual RMS currents in three phases by subtract-blocks. The outputs of the subtract-blocks are the RMS currents to be injected to respective phases, which after multiplying by $\sqrt{2}$ give the respective peak values. Amplitudes of reference signals are directly proportional to these peak values. Block diagram of reference signal generator is shown in Figure 18.

3.3.2 Calculate Phase Angle of Reference Signal

Reference signals are generated to be inphase with the load currents in respective phases. A Phase Lock Loop (PLL) block on respective feedback current extracts the phase-angle information, which after processing in a functional block generates unity-amplitude sinusoidal signal, inphase with load current. This sinusoidal signal is multiplied by the relevant amplitude of reference current to form the reference signal.

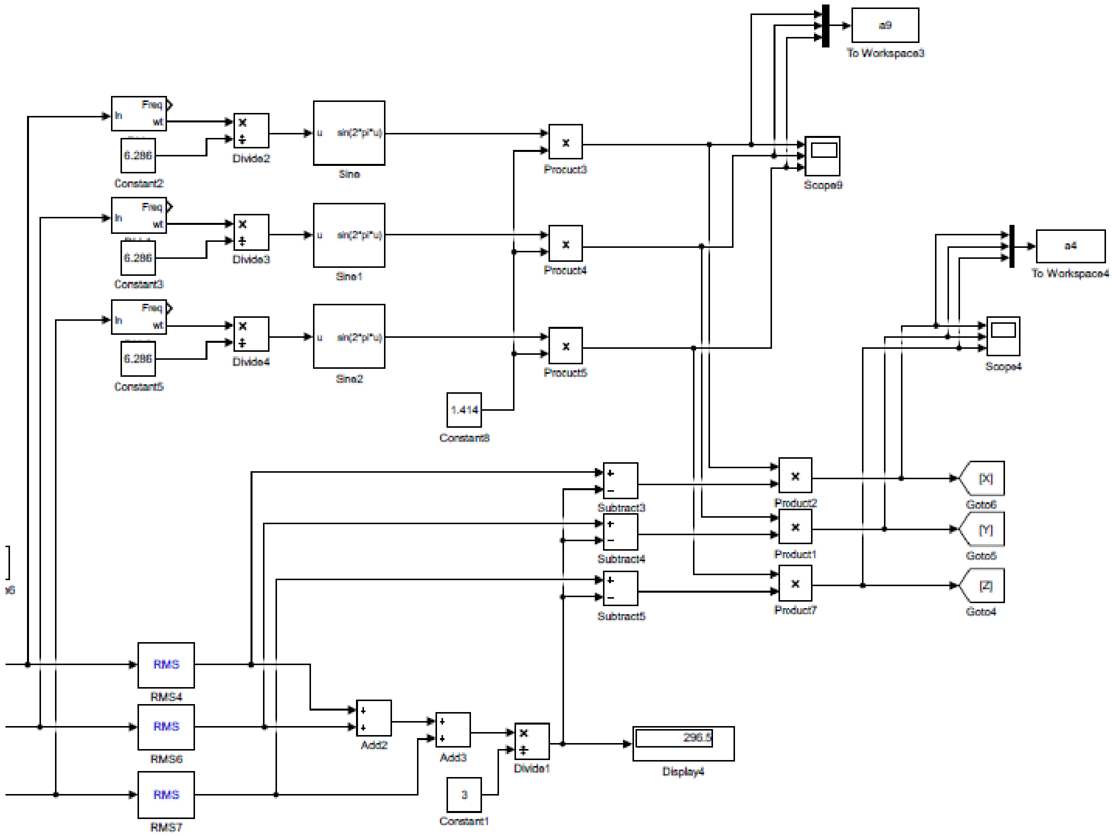

Figure 18: Mathlab Model of Reference Signal Generator

3.4 Designing of Switching Pattern

Switching patterns for power transistors of individual inverters are generated by the respective hysteresis current controllers according to the reference signal and the instantaneous current in that phase.

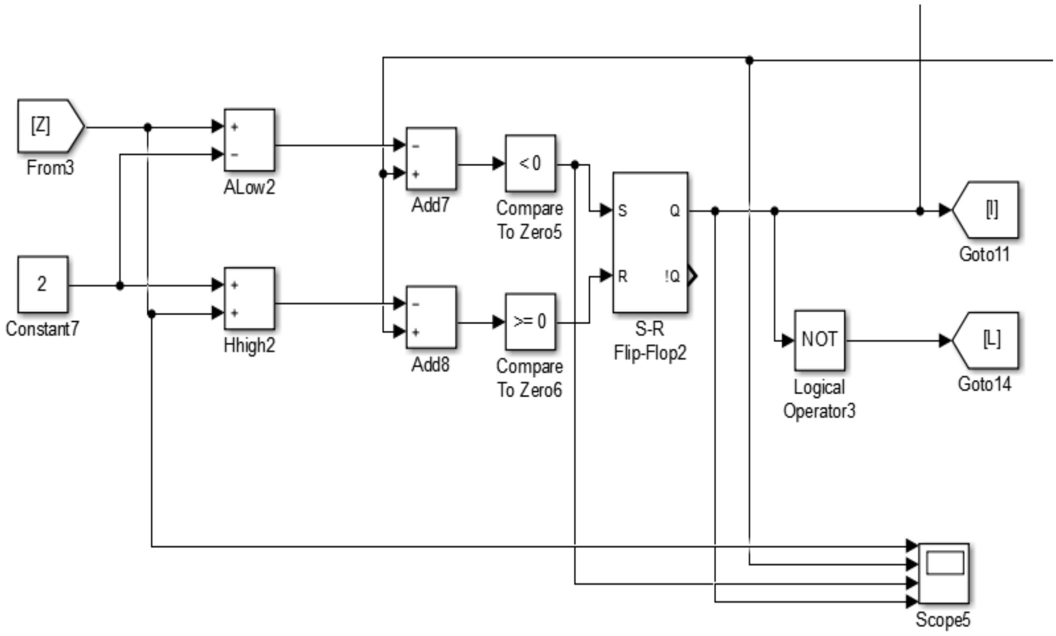

Figure 19: Mathlab Model of Hysteresis Current Controller

As stated before, the width of HB was decided as 4 A as a compromise between switching frequency and running-ripple of output current. Lower and upper boundaries of hysteresis band are generated by subtracting and adding HB/2 from and to the reference current. Two comparators detect whether the feedback current is falling below the lower boundary or rising above the upper boundary and change the switching state to reverse the falling or rising. Two S-R latches ensure that switching state is not changed at other times.

3.5 Design of Low Pass Filter

Switching frequency of the inverter is varying from 1 kHz to 4 kHz with the instantaneous ramp of the reference current wave signals. These switching frequencies tend to create noise in the voltage wave form at the point of common coupling. To minimize such noise, a capacitor was included between each line and the earth, which formed a first order LC low pass filter with the current controlling inductor at the inverter output. . The capacitors were sized to obtain a threshold frequency of 210 Hz. The values of capacitor and inductor were 140uF and 4mH respectively.

3.6 Matlab Model of Automatic Load Balancer

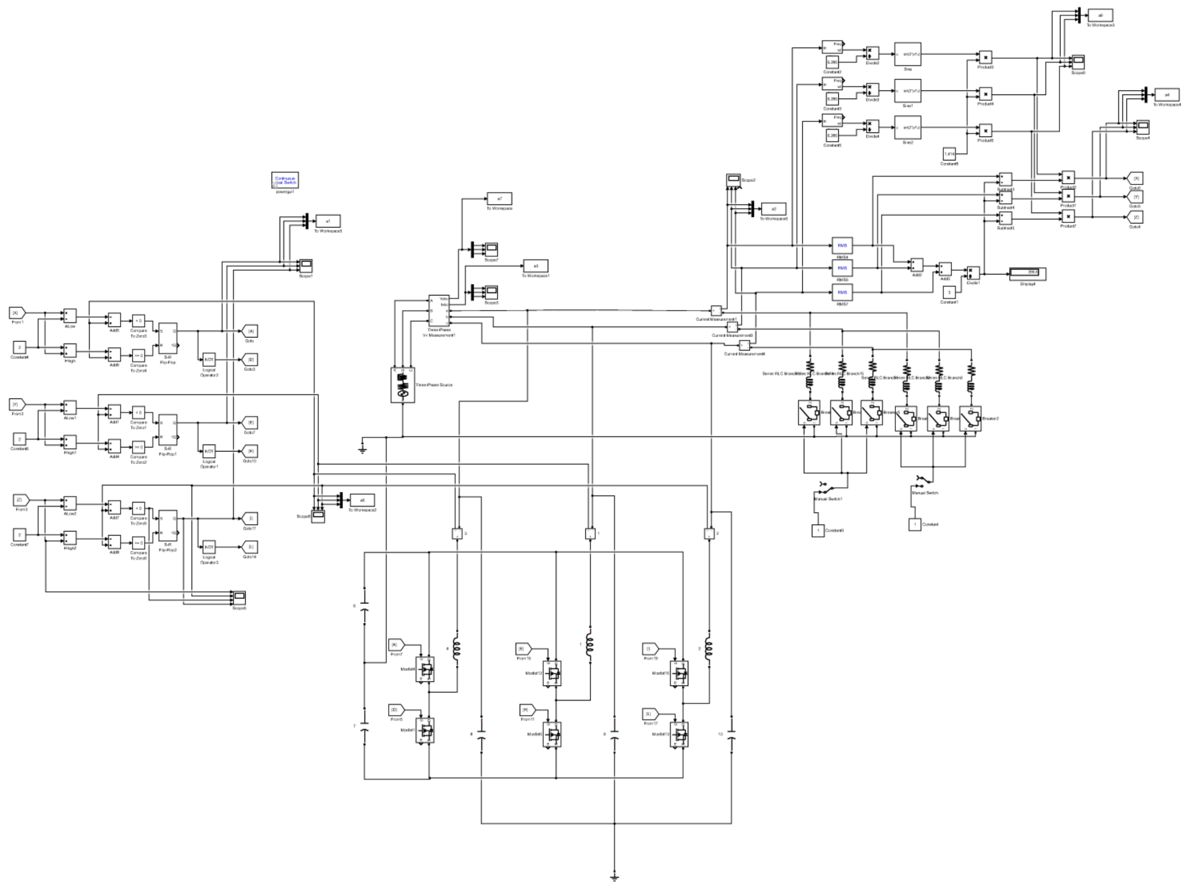

Figure 20: Mathlab Model of Automatic Load Balancer

MATLAB block of three phase source was used as distribution substation and a block of series RLC branches was used for the distribution load for this model. The parameters of RLC values were taken from the real data in the field study. The electrical parameters of 250kVA substation were included to the three phase source block. Some of the parameter values were taken from manufacture and others were calculated.

The parameters of the electronic components such as MOSFETs, inductors, capacitors were included in to the model to achieve real outputs and required technical parameters were taken from manufactures datasheet of selected components.

3.7 Fine Tuning With Real Values

3.7.1 Current Unbalance Level and Substation Capacity

To obtain accurate and realistic result, the parameters and figures used in the model should be accurate. Technical data, such as impedance of loads, substation parameters, MOSFET parameters and response times and other electronic components parameters were directly taken from respective sources. Load data were obtained from field studies and manufacture data sheets.

The data of distribution substation in Pannipitya Feeder 7 were collected and analyzed, and the loading factors are shown in Table 3. Average unbalance level of identified substation were around 25% and it varies up to 60% in few cases. When designing loads of the model, the above key figures were considered. Inductive loads were calculated by taking relevant data from previous field studies of distribution substation. Inductive loads of MATLAB model were adjusted to cover range of power factor from 0.6 to 1.00.

Table 3 : Summery of Data Analysis

Sin No		**P007**	**P078**	**P084**	**P087**	**P170**	**P012**	**P013**
Transformer Capacity KVA		160	250	250	160	160	250	250
Current Unbalance %	**Average**	16.08	28.13	15.60	15.34	26.19	15.51	26.49
	Max	31.75	47.01	50.59	30.47	59.03	38.56	43.22
	Min	2.65	2.37	0.89	1.86	0.51	2.57	14.69
Load KVA	**Average**	126.74	133.47	34.92	93.96	46.69	136.91	105.39
	Max	184.48	206.72	62.68	139.28	68.55	222.10	162.49
	Min	93.96	90.59	12.92	45.87	26.19	69.89	70.90

3.7.2 Transformer Parameters and Maximum Current of Inverter

100kVA, 160kVA and 250kVA are widely used capacities in distribution substations. For this study, 250kVA substation capacity was selected to cover all capacities. Relevant parameters of X/R ratio were taken from the manufacture. R value was calculated from manufacture's data and X value was deduced.

Average current unbalance percentage is identified to be around 25% with the worse case 60% for the selected sample. Therefore, the design should cater for 25% of current unbalance from 250kVA distribution transformers. Then the inverter should handle more than 75A unbalance currents. Considering safety margins, the inverter was designed for 100A current handling capabilities at normal operation.

Hence Power electronic components were selected to handle 100A current. MOSFETs are the main components that handle current of inverter. Series current-controlling inductor at the inverter output also handles the same 100 A current.

3.8 Parameter Design for Optimization

3.8.1 Maximum Switching Frequency

Switching frequency of inverter is mainly determined by the hysteresis band and the required ramp of current variations. When switching frequency is high the thermal losses of MOSFET goes high but injected current becomes closer to reference signal. So, it is required for optimization of thermal losses and the smoothness of injected current. Considering both factors, 4 kHz of maximum switching frequency was decided for the hysteresis current control inverter.

3.8.2 Threshold Value of Low Pass Filter

Injected current has ripples and spikes of 4 kHz frequency. Power frequency ist 50 Hz and above spikes will appear as distortions at power frequency. If threshold frequency of low pass filter is chosen near the value of power frequency the current tracking will be sluggish and the current diversion through the filter capacitor will rise. Also, size and cost of the capacitor and inductor will rise, which are not desirable. So considering quality of injected current, the change of phase angle, the size of the component and the price of the component, a threshold value of low 153Hz was selected.

4 MODEL ANALYSIS AND RESULTS

4.1 Test 1

The selected unbalanced loads consist of both resistive and inductive components with different power factors close to the unity. The selected unbalanced components are indicated in Table 4. The selected unbalanced load pattern was loaded to RLC branches in the Matlab model and the simulation was run for 300 ms as the first test case. It was observed that the percentage of unbalanced current of loaded parameters was 28.88% according to ANSI C84.1-2006 standard.

In the simulation, the currents 79.98A, 7.57A and -87.36A were injected to respective three phases and the transformer output current become balance as 302 A in each phase. If this unbalance continued through the whole year, the total copper loss due to unbalance alone would be 2403 kWh, which is substantial. The results are also indicated in the Table 4.

Table 4 : Loaded Distribution Load for test 1

		Phase R	Phase Y	Phase B
Load	Active(Ohm)	0.98	0.76	0.59
	Reactive(Ohms)	0.31	0.19	0.04
	Current	223.50	293.74	388.75
	Angle(deg)	17.76	13.92	4.26
	Power Factor	0.95	0.97	1.00
	Unbalance %	28.88		
Injected Current by Inverter (A)		79.98	7.57	-87.36
Energy losses per year(kWh) (Copper loss due to unbalance alone)		2403		
Total Load (kVA)		207.92		
Transformer Load after Balanced (A)		302.48	301.41	300.34

4.1.1 Unbalanced Load Pattern

As indicated above the simulation of an unbalanced load pattern was run for 300 ms and the relevant three-phase currents indicated in three colors. An unbalanced current pattern was measured in the load side and plotted in three colors in Figure 21.

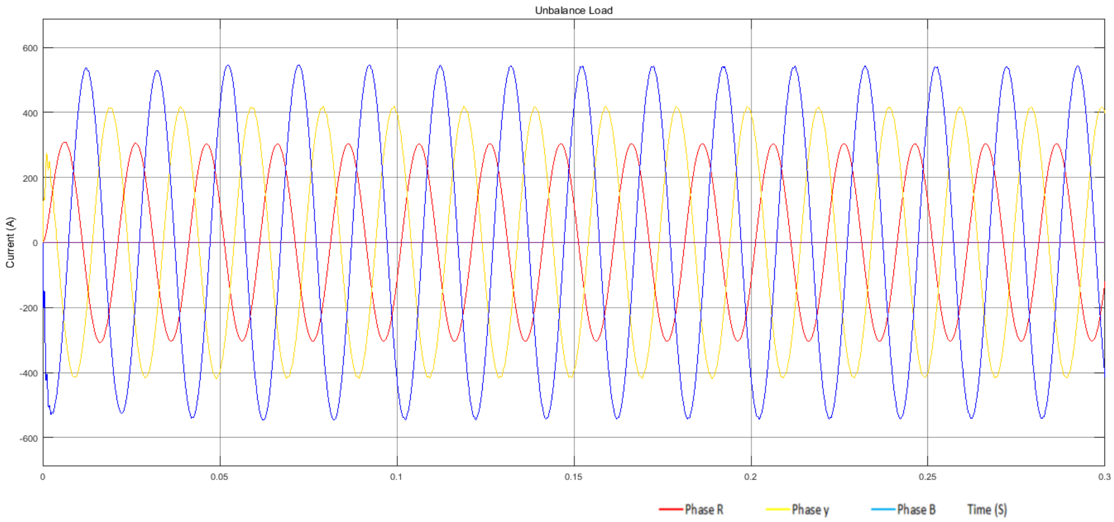

Figure 21: Current Profile before Balancing

4.1.2 Balanced Load

After balancing the transformer load currents are plotted in figure 22. The first cycle (20ms) of Figure 22 is the initialization time of the inverter used for measuring the rms current in the load pattern and to calculate unbalanced current in each phase. In the second cycle (20-40) ms is the initialization time for load balancing. After 40 ms from the starting, the load balancer performed as expected maintaining balanced three-phase loads. Hence within one cycle of time, the load balancer could balance the unbalanced load as shown in Figure 22.

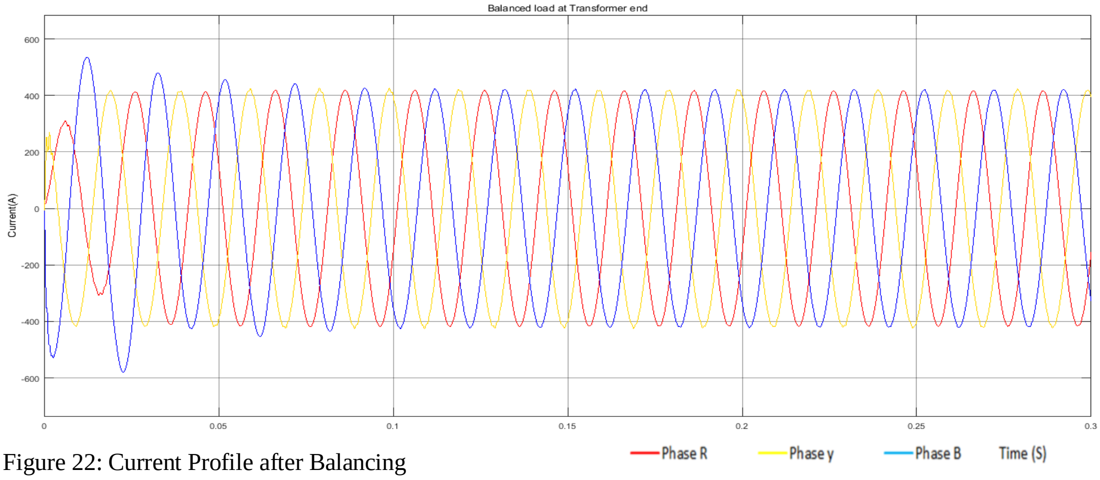

Figure 22: Current Profile after Balancing

4.1.3 Injected Current

The injected currents of three phases are shown in Figure 23. In the first cycle (0-20ms) is shown as zero current, this was initialization time of automatic load balancer. In second cycle (20-40 ms) the inverter started to inject and draw the current for balancing the load in a distribution substation. At the end of the second cycle, automatic load balancer achieved the expected target. Within 20ms, this inverter is capable of balancing the unbalanced load in the distribution substation. The injected currents of three phases are shown in Figure 23.

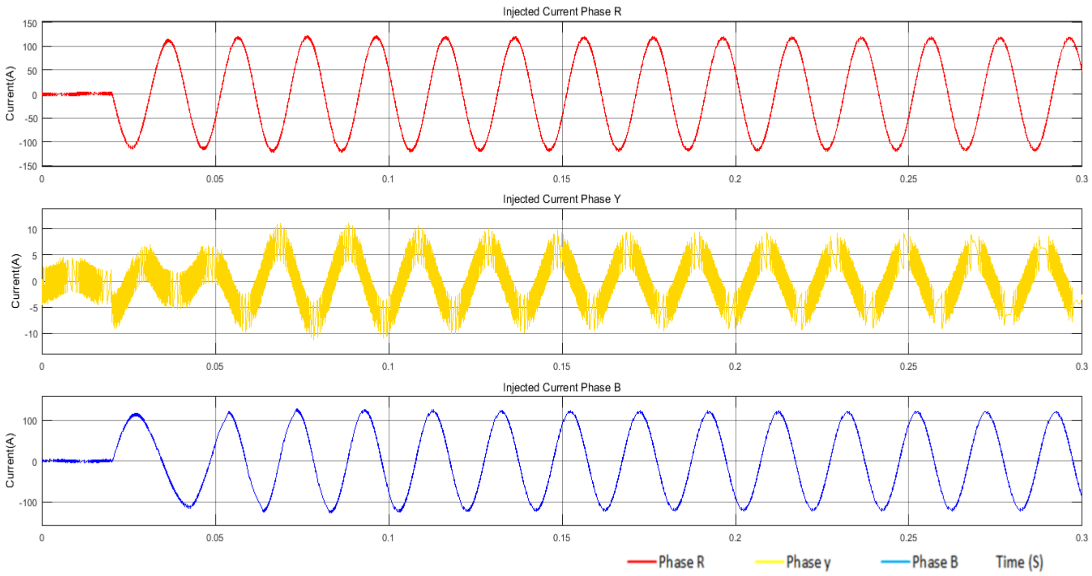

Figure 23: Injected Current

4.1.4 Switching Pattern

The hysteresis band current controller switches according to the reference current signal and the width of the hysteretic band. The switching frequency will change instantaneously with reference to the amplitude of the current flow and the rate of change of current (current ramp dI/dt). In the first 20ms (initialization time) switching patterns in 3 phases are more equal and near to zero.

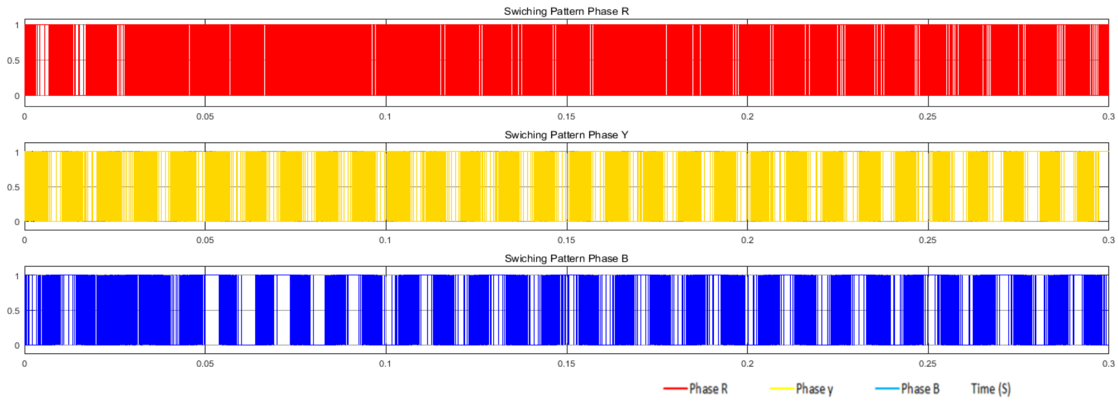

Figure 24: Switching Pattern

4.1.5 The Referance Signal

Figure 25 shows the performance of a current wave profile of the hysteris band current controller. The reference signal which is generated by the current unbalance calculator is sent to the HBCC. According to that, it makes switching pattern considering threshold values of Hysteris band and shown in Figure 25, named as "threshold switching pattern". This threshold switching pattern was the input signal to SR flipflop and it makes switching patterns to MOSFETs. This switching pattern is shown as a "switching pattern" in the Figure 25. Transistor ON and OFF times are decided by the reference signal and injected current waveform which stays the limits of Hysteris band. The injected current is shown in the Figure 25. If the inverter performs well, the injected current waveform should be a more similar to reference signal with the limit of defined hysteresis band. If more accurate figures are required, hystris band may be reduced. When reduced hysteries band exist, switching frequency will increase and thermal losses of transistors will be increased and it affects the efficiency of the inverter. The first cycle, is initialisation period and after the second cycle it is more close to operate with the reference signal. Figure 25 shows that after one cycle of reference signal the inverter could be performing as expected.

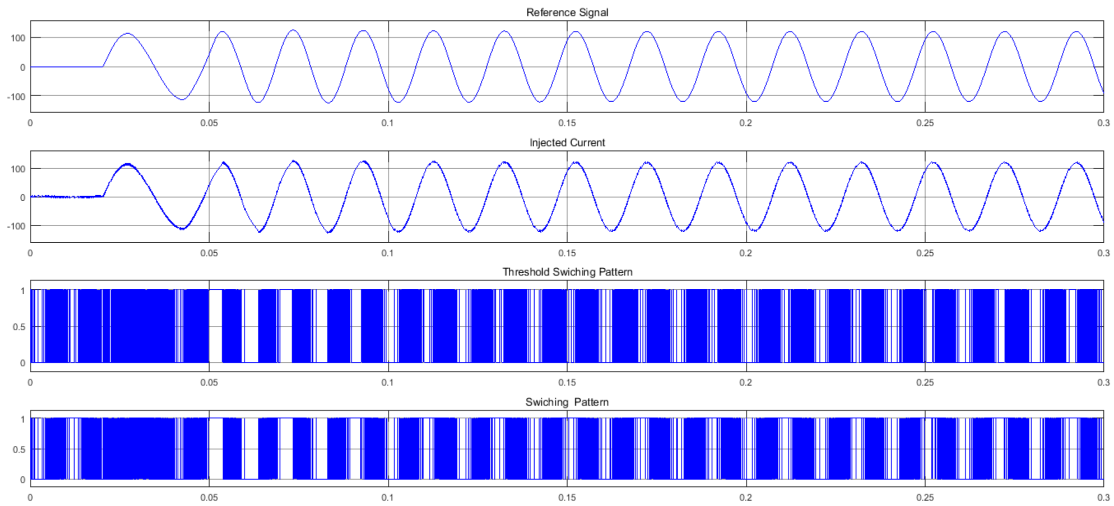

Figure 25: Performance of Hysteresis Current Controller

4.1.6 The Extracted Current Signal of Load Current

Figure 26 shows the extract current signal profile from the load current. The signal of load current sent to Phase Lock Loop (PLL) to capture the instantaneous angle of load current and make waveform according to the angle of PLL. The peak value of the amplitude is taken as 1.0. In the first cycle, it is initialization time and, from second cycle it starts to operate individually and it is normalized at the end of second cycle. After multiplying the amplitude by the unbalance current it generates reference current signal in to the hysteresis band current controllers.

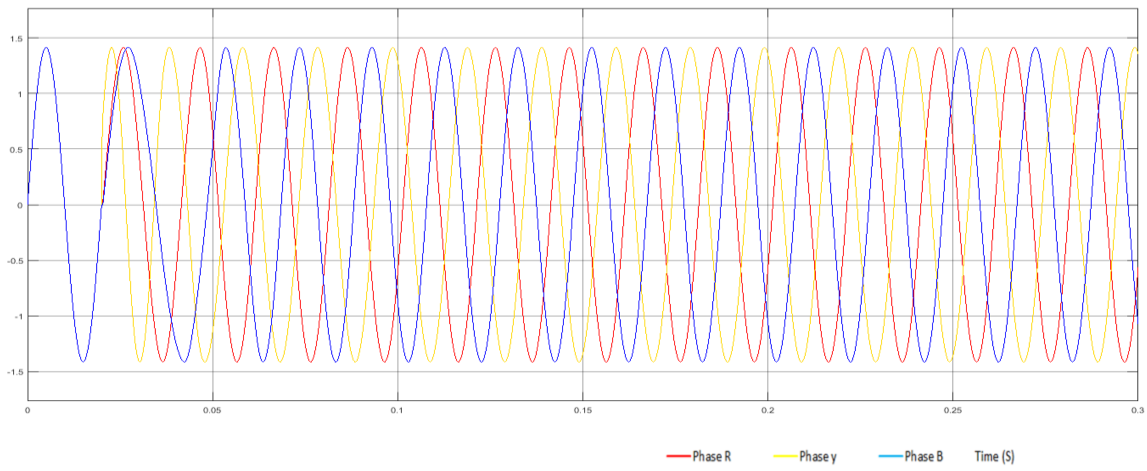

Figure 26: The Extraction of Load Current Profile

4.1.7 Voltage Profile

This inverter inject currents to the main power source that having 50-Hertz power frequency. Therefore switching frequency of the inverter is varying up to 1 kHz to 4 kHz. Both reactive components and active components are included to the model in the distribution substation and the load to develop more realistic outputs. Due to the above reactive components, it makes voltage ripples and waveform distortion in voltage profile at the common coupling point. To avoid that, a low pass filter was used to get a smooth voltage profile. After applying low pass filter, the waveform captured and plot in Figure 27. The ripples and distortions cannot be zero and can be optimized with the requirement.

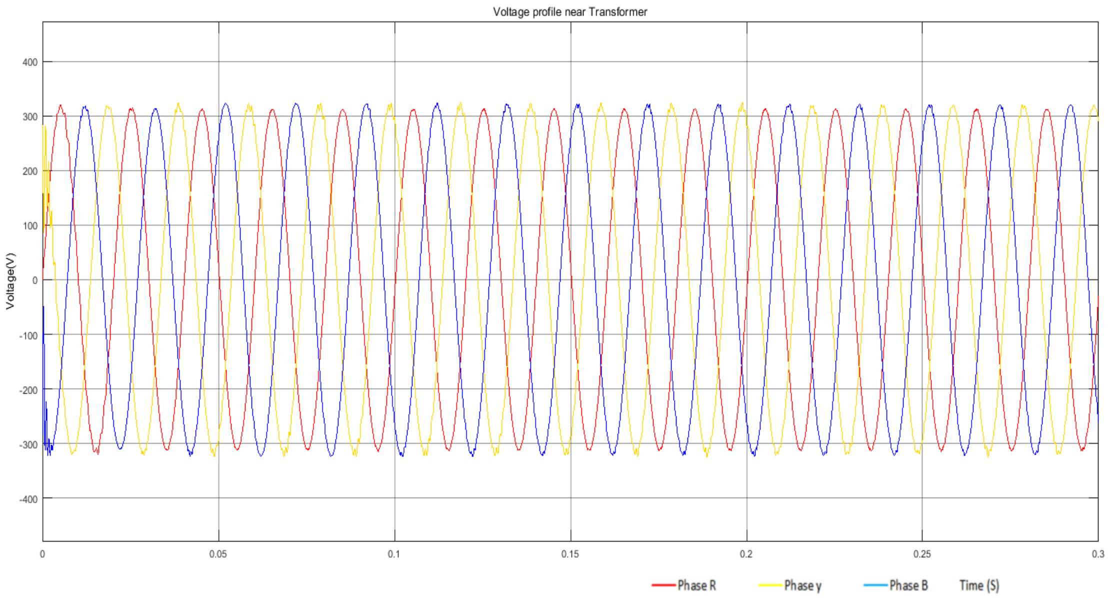

Figure 27: Voltage Profile at CCP

4.1.8 Summary of Test Case 1

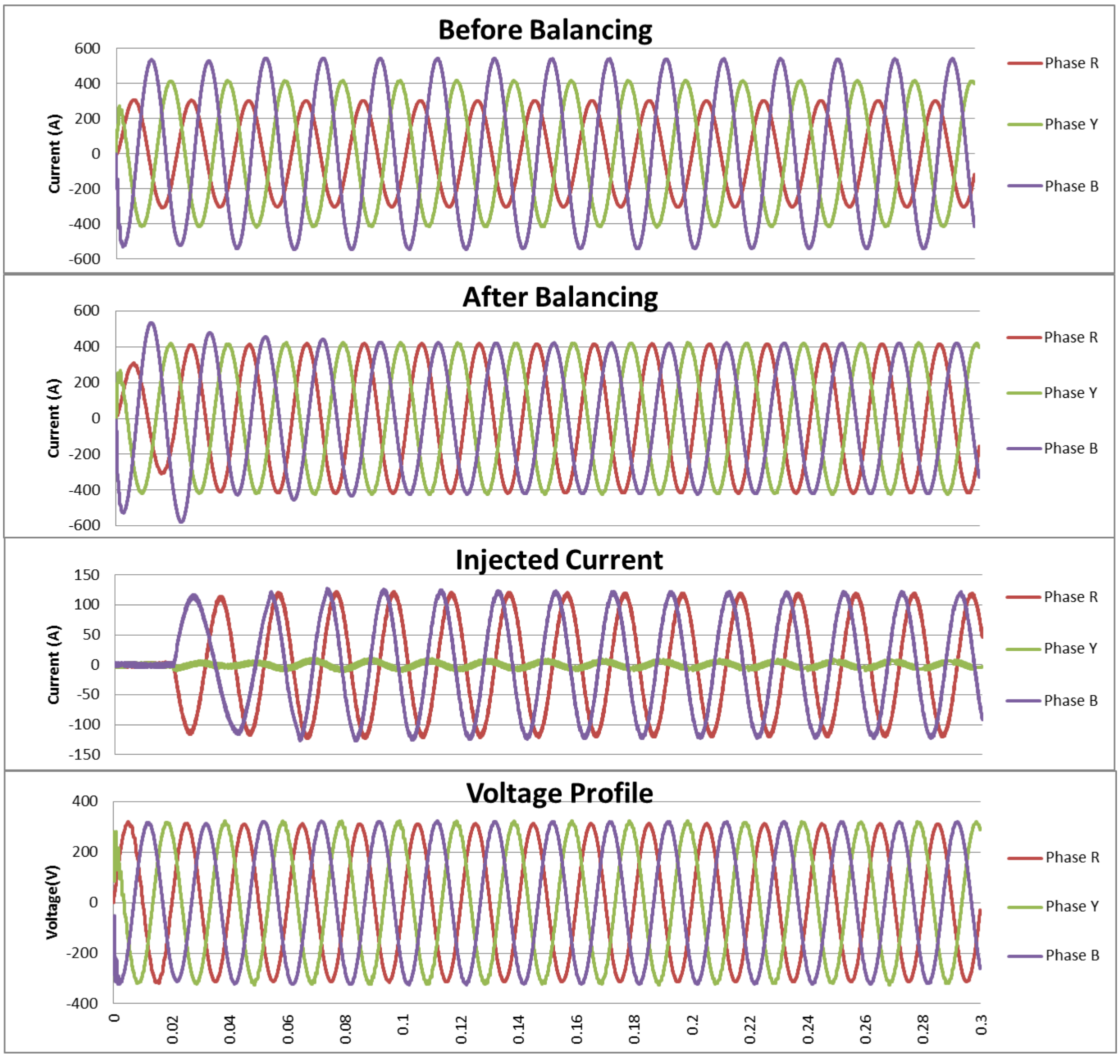

Figure 28: Summery of Test Case 1

Details of unbalanced load, balanced load, injected currents, and voltage profile at point of common coupling are plotted in Figure 28 for easier comparison. After the first cycle, inverter stared to inject currents and, at the end of the second cycle it performed as expected.

4.2 Test 2

The capability of dynamic variation in current balancing was evaluated by this test. Two load patterns were loaded to the model and it was simulated in defined time slots to checked performance at dynamic variations in load balancing.

In test 1, stable load balancing capability was checked on defined time slot. But in the real cases, the load pattern changes dynamically. To achieve best performance it was tested by using dynamic load pattern under the test case 2. Defined two load patterns were run in two separated time slots. The first 230ms simulated one load and the next 170ms simulated another load pattern and checked the behavior of two load paten changing points. The loads patterns were shown in Table 5. In that test, phase B load current reduces from 240A to 100A and the other two phases increase the current by 10A and 28A respectively. Relevant power factor was changed from a considerable amount at the load changing point, all relevant information is shown in Table 5.

Table 5 : Loaded Distribution Load for Dynamic Performance

		First Section (20-230)ms			Second Section (230-400)ms		
		Phase R	Phase Y	Phase B	Phase R	Phase Y	Phase B
Load	Active(Ohms)	1.71	1.31	0.85	1.20	0.90	1.88
	Reactive(Ohms)	0.79	0.63	0.44	1.26	0.85	1.29
	Current	122.24	158.32	240.35	132.40	186.02	100.94
	Angle(Deg)	24.65	25.60	27.34	46.29	43.27	34.39
	Power Factor	0.91	0.90	0.89	0.69	0.73	0.83
	Unbalance %	42.05			38.48		
Injected Current by Inverter (A)		-53.19	-14.18	67.38	-7.09	47.52	-39.01
Energy Losses per year (kWh)		1283.6			662		
Load (kVA)		119.82			96.05		
Transformer Load after Balanced (A)		174.71	173.45	173.64	140.18	139.42	139.87

4.2.1 Unbalanced Load

Both load patterns are plotted in Figure 29 and the changes of load variation noticed at 230ms from starting.

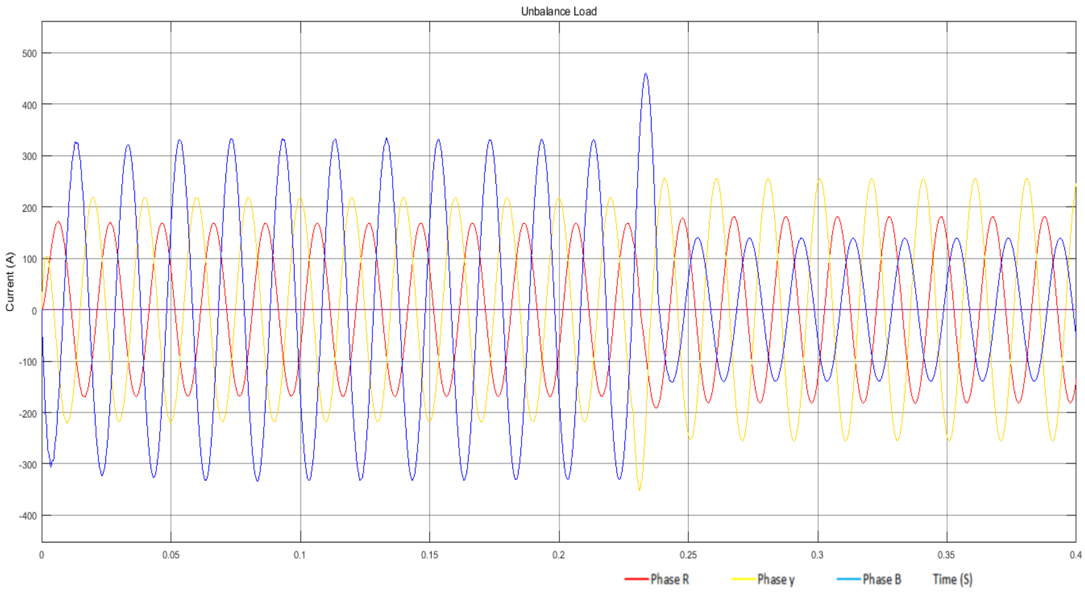

Figure 29: Load Before Balancing

4.2.2 Load Pattern after Balancing

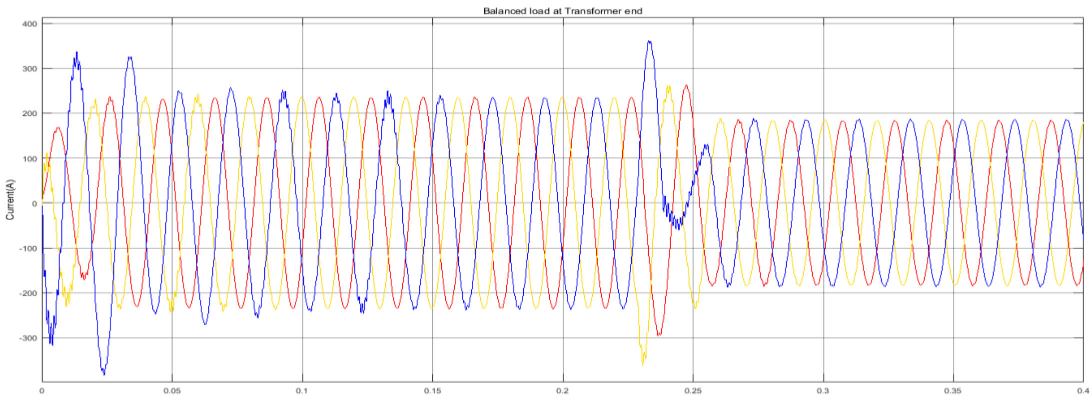

Figure 30: Load After Balancing

The first cycle is the initialization time of the inverter and the second cycle is the load balancing time. After that, it was running in normal condition. After switching to the second section of the load, pattern was balanced within one cycle. The second section is running at a very low power factor and this inverter can perform at very low power factor as well.

4.2.3 Injected Current

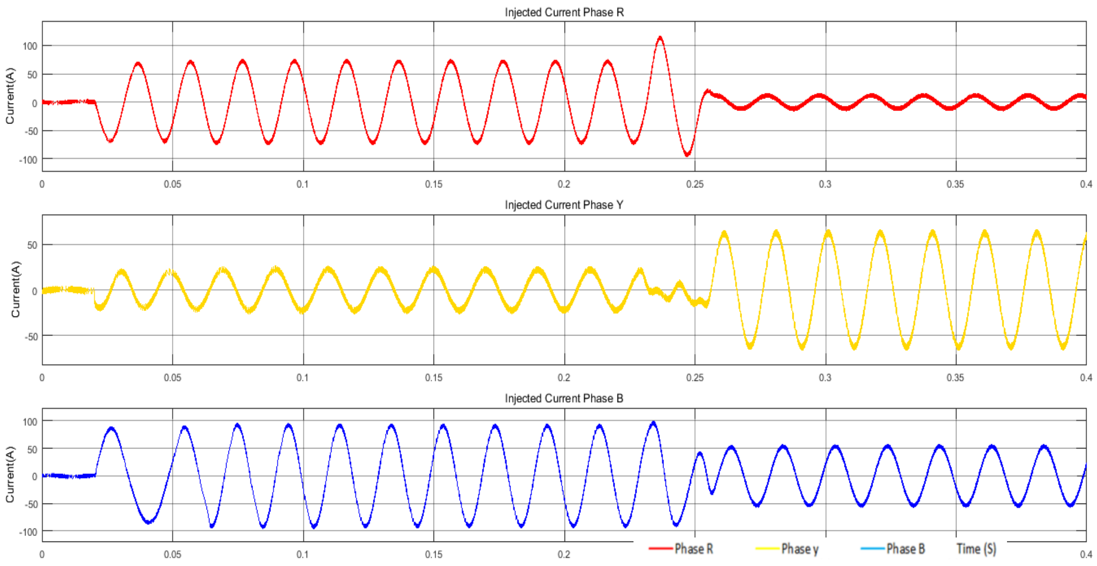

Figure 31: Injected Current

Changes of injected current in three phases are plotted in Figure 31 and the behavior of load changing point can be noticed at 230 ms after starting.

4.2.4 Switching Pattern with Reference Current Signal

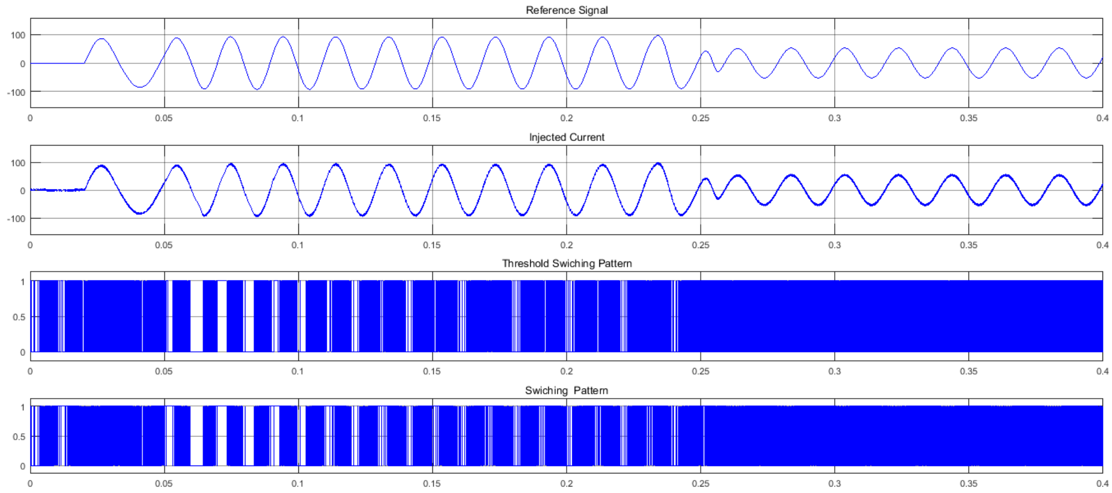

Figure 32: Performance of Hysteries Current

The similarities and deviation of injected current and the reference current signal are shown in Figure 32 and respective switching patterns are also plotted in Figure 33.

4.2.5 Switching Pattern

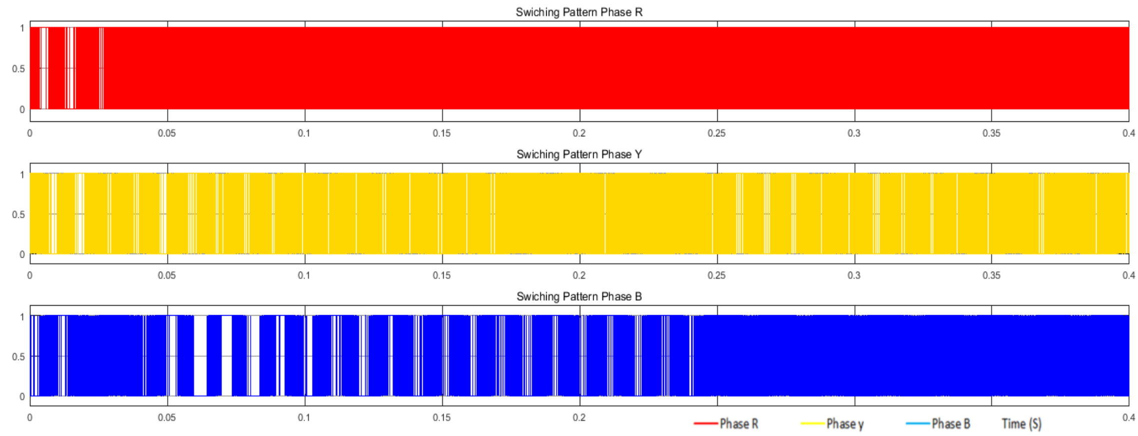

Figure 33: Switching Pattern

4.2.6 Reference Current Signal

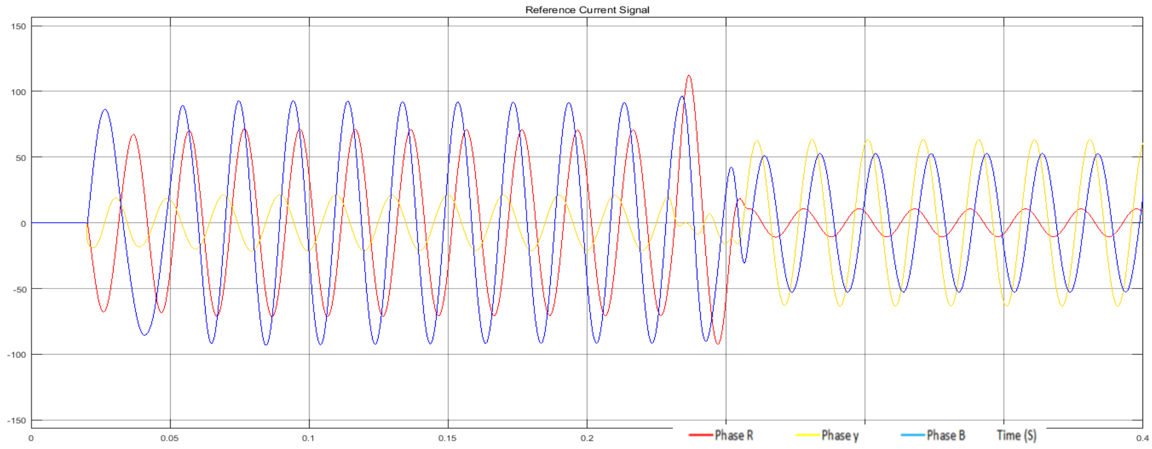

Figure 34: Reference Signal

4.2.7 Voltage Profile of Common Coupling Point

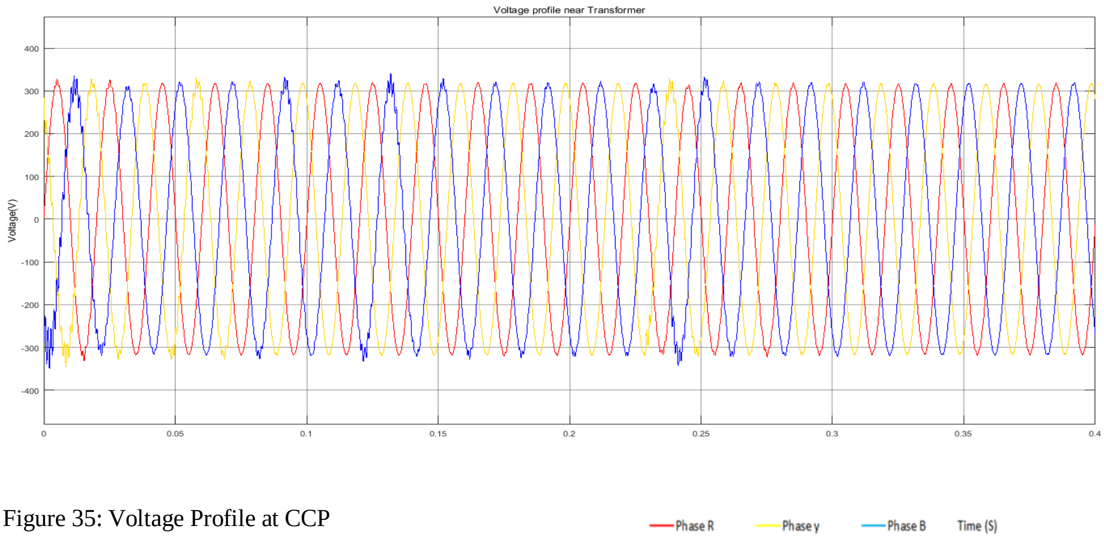

Figure 35: Voltage Profile at CCP

When current injected to the network it made some distortion due to switching frequency, as per the designed requirement, the voltage distortion at the common coupling point should be minimized to provide quality power supply. For this requirement, automatic load balancer used low pass filters for injected current to mitigate high-frequency current signal and to make proper sinusoidal current and voltage waveform.

4.2.8 Summary of Test Case 2

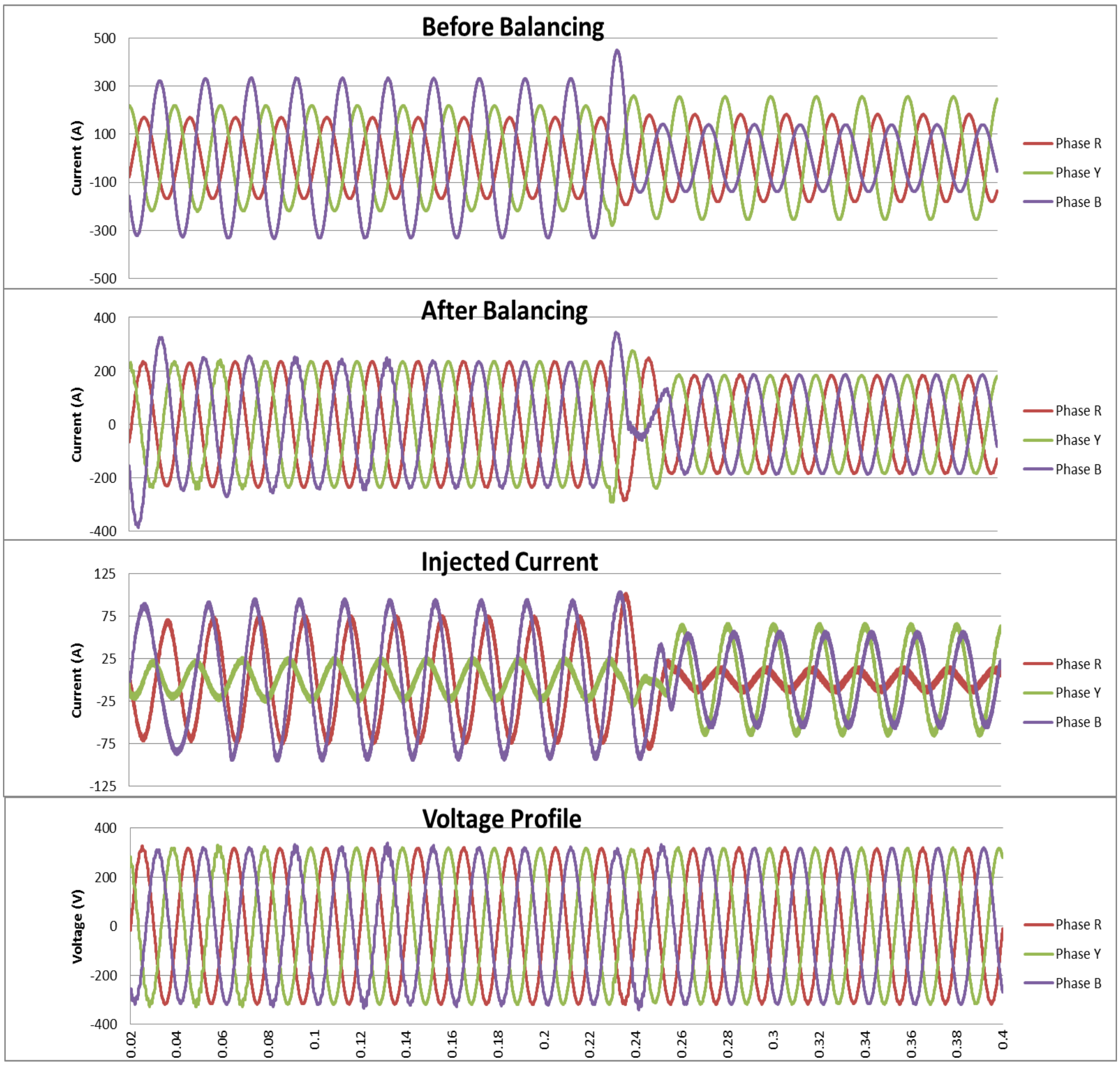

Figure 36: Summary of Test Case 2

5 DETAIL DESIGN OF AUTOMATIC LOAD BALANCER

In addition to the MATLAB model the detail design was carried out for cost estimation of the Automatic Load Balancer. The consistency of the detail design and its specifications are shown below.

- Design of inverter
    - Design of gate drivers
    - Design of protection
    - Design of power supplies
- Design of main controller and other accessories
    - Features of Microcontroller and other accessories

5.1 Schematic Diagram of Automatic Load Balancer

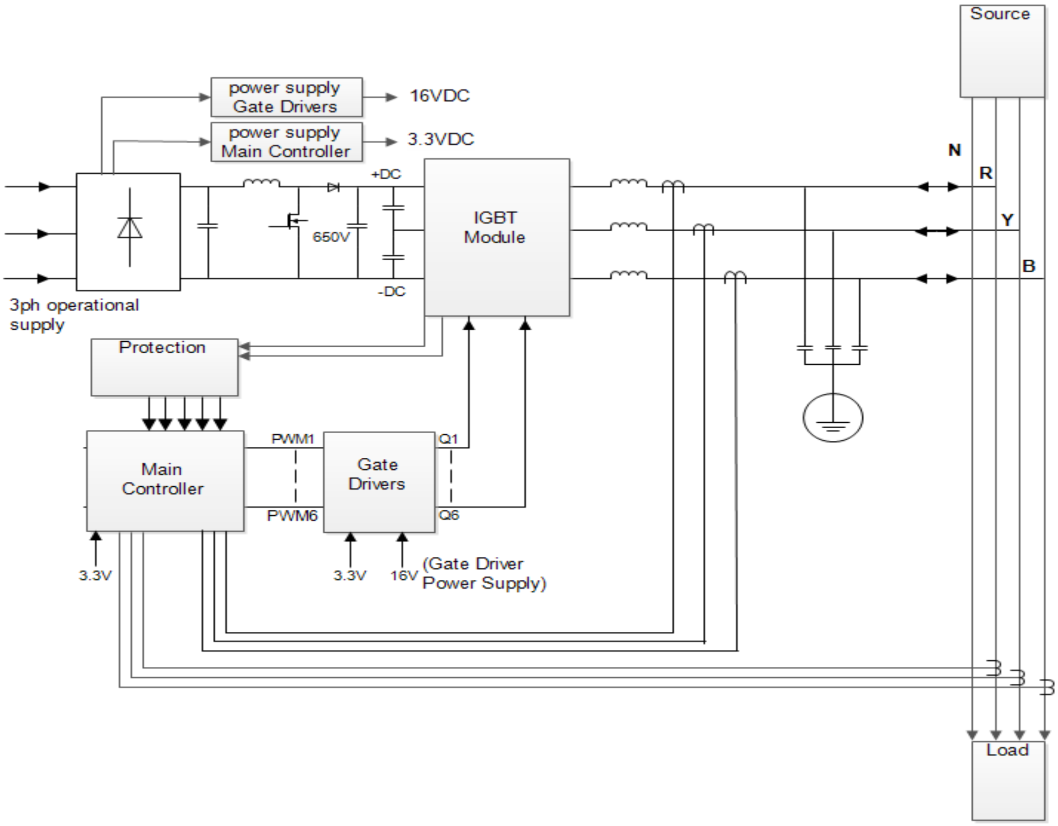

Figure 37: Schematic Diagram of Automatic Load Balancer

Detail schematic diagram of an automatic load balancer is shown in Figure 37 and it consists of main sections such as distribution substation, loads and the automatic load balancer. Power supplies, IGBT modules, main controller, gate drivers, protection devices, filters and current measuring components are main subsections of the automatic load balancer.

5.2 Design of Gate Drivers

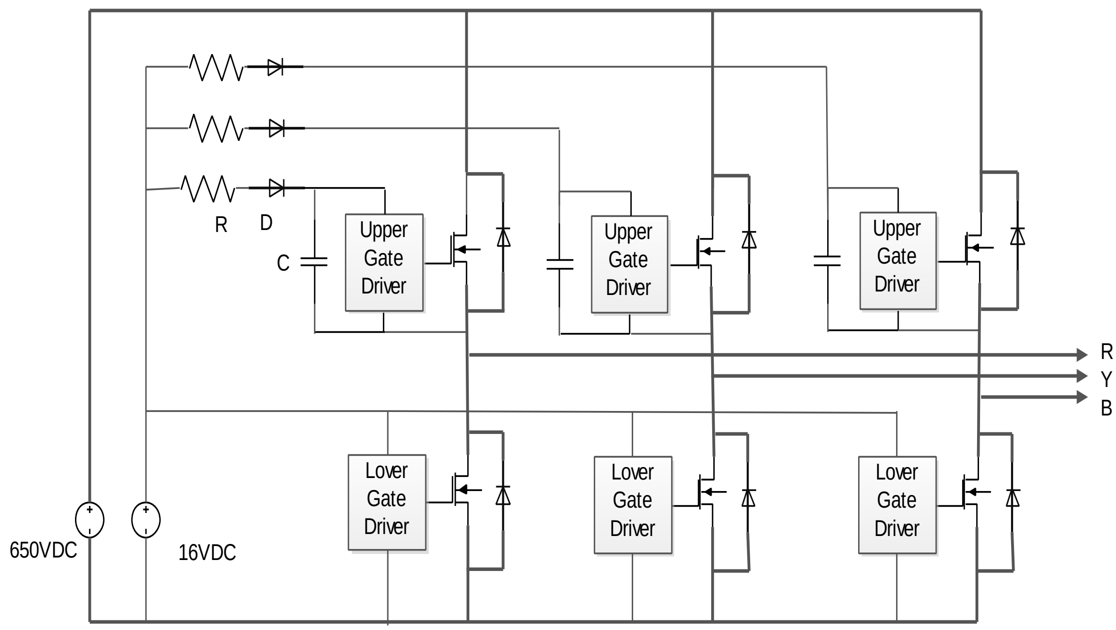

Figure 38: Gate Drivers

A 650V DC link was designed to power up the MOSFET module that consists of separate three H Bridges. The drain terminal of upper MOSFET and source terminal of lower MOSFET directly connected to the DC-link positive polar and negative polar respectively. The voltage of interconnected source terminal of upper MOSFET and drain terminal of lower MOSFET is switched to 0V and 650V according to switching pattern of gate drivers. Upper MOSFET and lower MOSFET are switched ON and OFF with respect to the provided gate voltage in MOSFETs. The signals of gate drivers are provided by main controller as per the switching algorithms. The voltage source of the main controller should be more accurate and stable. The main controller and MOSFETs are operated in different voltage levels of 3.3V and 650V respectively. The specialty of the gate drivers is not only the interconnection; it provides voltage isolation and protections systems. The operating voltage of gate drivers is set on another voltage level. The main scope of gate drivers is the arranging the protection of switching equipment, adjusting the switching timing and ensuring the voltage isolation in communications.

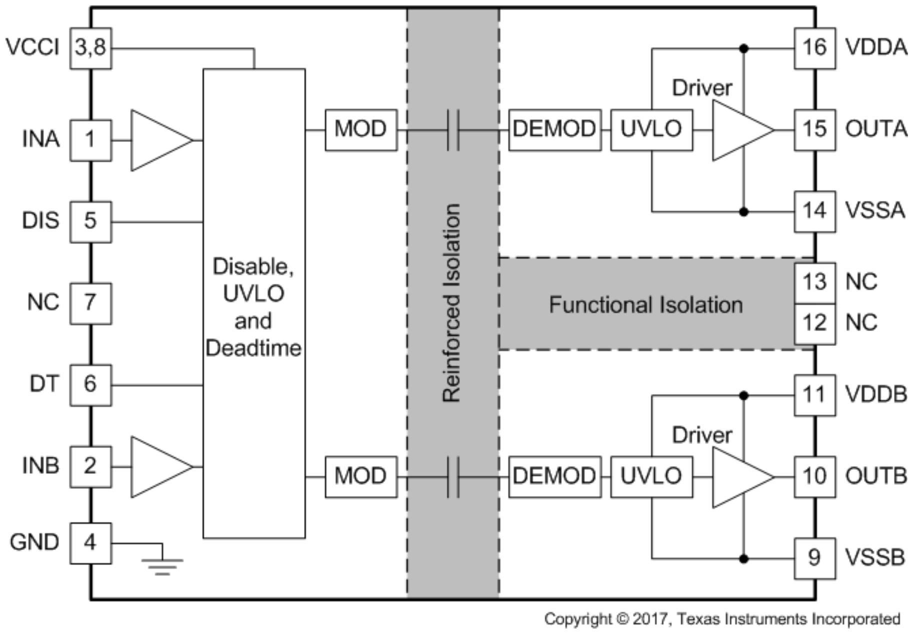

Figure 39: Gate Driver Chip UCC 21520 Texas Instrument

The gate driver chip UCC 21520 manufactured by Texas Instruments is selected for this design by evaluating technical specifications. It consists of three inbuilt isolating components such as top gate drivers, bottom gate drivers, and logic controller. The main objective of the logic controller manage the protection of top and bottom MOSFET by avoiding switch on both at the same time. Every MOSFET or IGBT has delays in switching ON and OFF. Therefore, it is ended up in a damage to H bridge MOSFETs when both are turned on at the same time due to one of the switching OFF delay. So this logic controller consists of dead time insertion protection, Programmable dead time, and integrated interlock for protecting the H bridge MOSFETS from ON and OFF switching delays.

Programmable dead time is programmed by an external signal and it enables and disables MOSFETs. The dead-time insertion protection is programmable protection to avoid damages to MOSFETs by delays of a switch ON and switch OFF. Dead time delay can be programmed by calculating the relevant resistor and capacitor values considering the information of turn-on delay, turn-off delay, and the maximum switching frequency of selected MOSFETs.

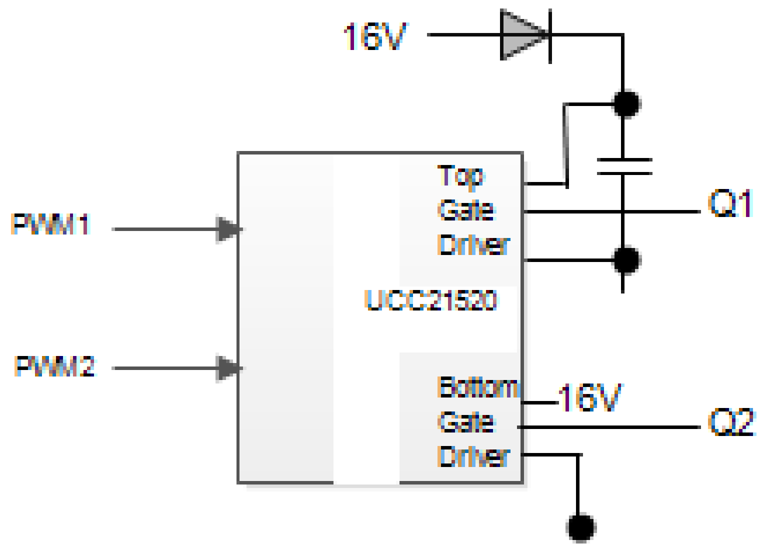

Figure 40: Bootstrap Driver

For the design of power supply for the top and bottom gate drivers, it is necessary to consider the voltage range in the switching of H bridges. The switching arrangement changes the reference voltage of the source terminal in top and bottom MOSFET. One of the most popular and cost-effective ways for designers to do so is the use of a bootstrap circuit which consists of a capacitor, a diode, a resistor, and a bypass capacitor.

5.3 Operation of Bootstrap Power Supply

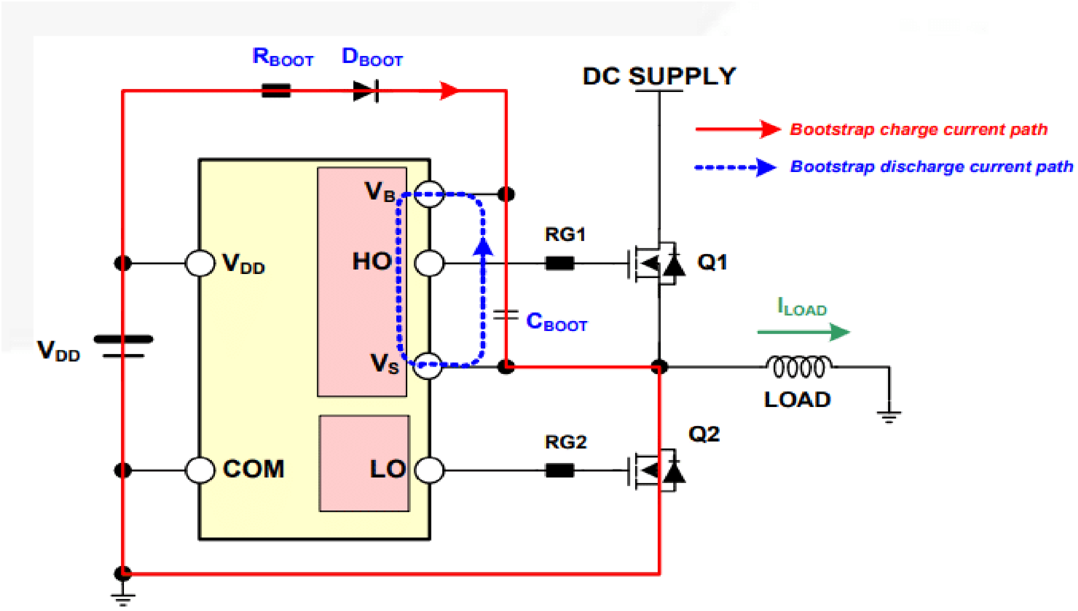

Figure 41: Bootstrap Operation

When the low-side MOSFET is turned ON, the high-side MOSFET turns OFF. The current of bootstrap power supply flow through the resistor, diode and charge the capacitor of high side. The capacitor should be capable to store required energy for operation of top gate driver, and the resistor value should be suitable to control current flow to charge capacitor during switch ON time. Maximum switching frequency shall be considered for calculating switching time and resistor values. When calculating the size of the capacitor, it took into account the minimum switching frequency and required current and voltage to switch on upper MOSTET. The capacitor shall be discharged at the moment of the turning ON of top gate drives and the diode become reverse biased. When selecting the diode it is necessary to calculate reverse-biased voltage, operating voltage and forward-biased current while turn ON of upper MOSFET.

5.4 Design of Protection

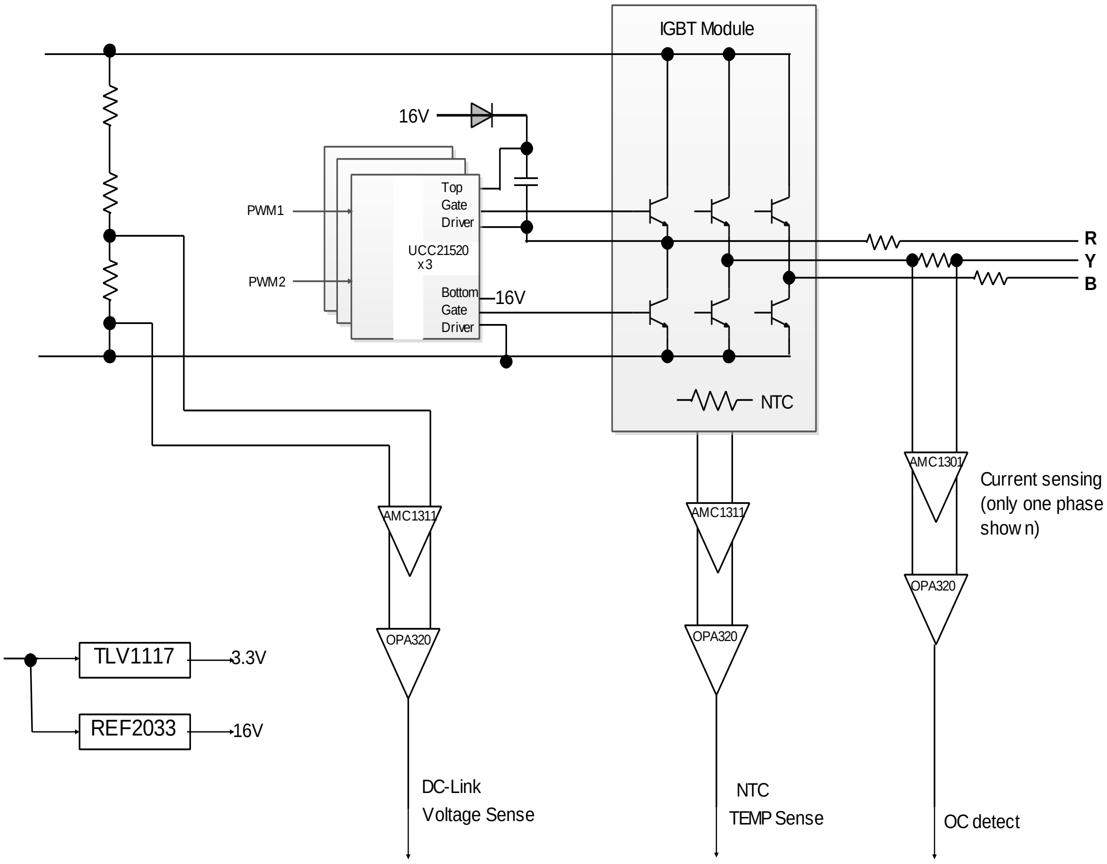

Figure 42: Protection Scheme

This design consists of basic protection including overcurrent, over temperature of MOSFET, and DC link voltage sense. For the overcurrent sensing, it uses a shunt resistor or current transformer with analogue signal amplifiers having lower noise. Main controller monitors the analogue signal of over current by comparing with programmable over current settings.

MOSFET modules are the most expensive component of this inverter and operating temperature is a key factor for life expansion of the MOSFET modules. Hence signal of NTC temperature sensors are used for the thermal protection of MOSFET modules. Low noise OP-AMP was used to amplify temperature signal into measurable scale and it is sent to the main controller through analogue to digital converter.

DC link voltage of MOSFET should be constant and stable since injecting current vary when changing the DC link voltage. DC link voltage was controlled by switching arrangement of MOSFETs in bootstrap power supply and its voltage was measured by the voltage divider connected to OP AMPs through the analogue to digital converters by the main controller.

5.5 Design of Power supplies

An automatic load balancer required a few power supplies for various purposes.

- 650VDC supply
- 16VDC Gate driver power supply
- 12/5VDC supply
- 3.3VDC

For the initial charging and building up of DC link voltage, it requires 650V DC external source power supply. AC Three-phase external source supply was converted to DC and it steps up by bootstrap power supply at 650 VDC.

Gate drivers operated with separately isolated DC supply of 16 V.

5.6 Selection of Micro Processor

5.6.1 Number of PWM channels

Six PWM channels or digital output are required for the drive MOSFETs through gate drivers.

5.6.2 Number of A/D Converters

Analogue to digital converters are required to measure the current inputs and measure protection signals. For the automatic load balancer, it required six A/D converters to measure load current and injected current in each phase, three A/D converter for over current, two for DC voltage link, and thermal protection. It requires eleven A/D converters.

5.6.3 Clock Speed

The maximum switching frequency of this inverter is 4 kHz and required to switch six PWM channels in parallel. Current measuring A/D converters operate in parallel in order to get more accurate results and algorithms need to operate as much as possible. So for the above requirement clock speed should be more than 20 MHz frequency.

5.6.4 Number of Input/output Channels

Other communication and operation it required six digital inputs and outputs.

5.7 Microcontroller

For the purpose of above requirement, The Microcontroller-AT91SAM3X8E was selected with ARDUINO DUE for the above requirement and its specifications are shown below.

Operating Voltage	3.3V
Input Voltage (recommended)	7-12V
Input Voltage (limits)	6-20V
Digital I/O Pins	54 (of which 12 provide PWM output)
Analog Input Pins	12
Analog Outputs Pins	2 (DAC)

Total DC Output Current on all I/O lines	130 mA
DC Current for 3.3V Pin	800 mA
DC Current for 5V Pin	800 mA
Flash Memory	512 KB
SRAM	96 KB (two banks: 64KB and 32KB)
Clock Speed	84 MHz

5.8 Layout Plan of Automatic Load Balancer

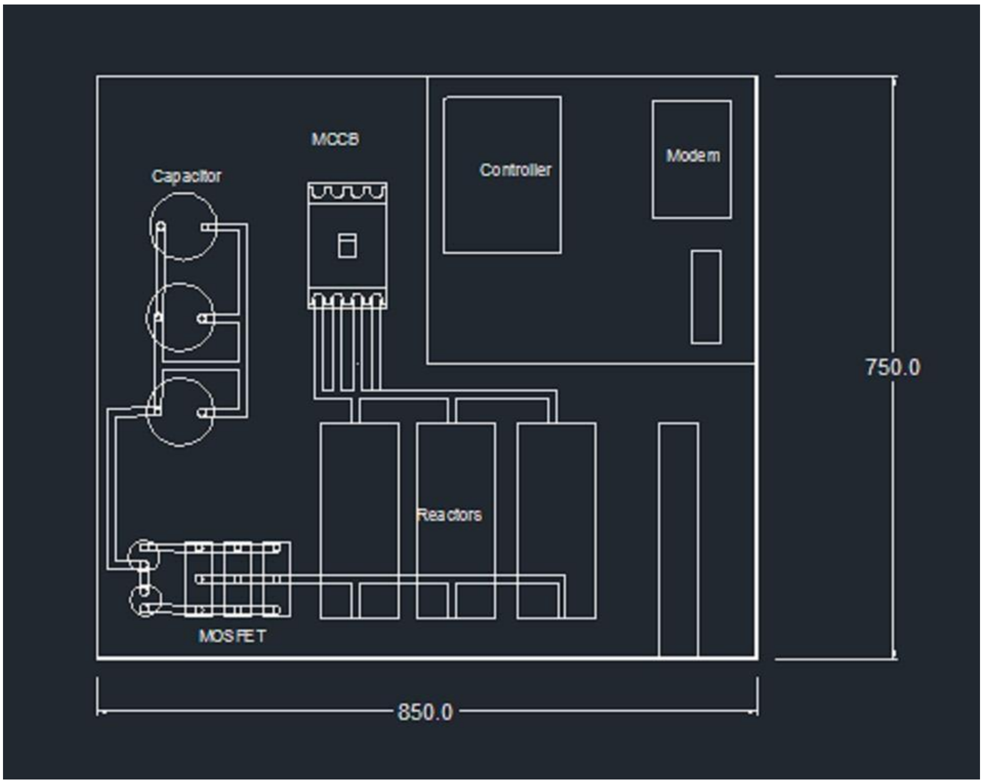

Figure 43: Component Placement Diagram

6 ECONOMIC ANALYSIS OF AUTOMATIC LOAD BALANCER

Transformer load unbalancing is one of the main solutions in the distribution network. Most distribution networks are manually rearranged their single-phase loads until balancing of the load currents are achieved. However, this method is not a feasible or efficient for this problem. Due to that automatic load balancer is proposed in this research and it should be economically viable for success as a viable project.

6.1 Savings by Automatic Load Balancer

Table 6 : Financial Benefits

	Savings	Saving per year in LKR
1	Copper Losses due to current unbalance	25,000
2	Increases of transformer life	Not Quantified
3	Cost of Manual load balancing	120,000
4	Can be used as Active power filter	Not Quantified
5	Effective utilization of existing equipment	Not Quantified

An average copper loss due to current unbalanced in 250 kVA loaded distribution transformer is around LKR 25,000.00 per year (assumption; the unit cost is LKR18.00, per kWh. The data source is few transformers in Pannipitiya Feeder 7).

Transformer current unbalance causes an increase of the vibration in the lamination of the transformer core and buildup uneven heating and heating spots in the transformer winding. As a result of it, the transformers expected life is reduced. The advantage of transformer life expansion cannot be quantified with available information.

The manual transformer load balancing is planned to cover each of the distribution substation at least once a year in the annual maintenance plan. Single-phase distribution load rearrangement is the method used for the distribution load manual balancing. Expertise knowledge, considerable labor, and materials are required for this trial and error method. In most of the cases, this method has been identified as an inefficient method because its results are not optimal and realistic due to the unpredictable behavior of load patterns. However, the total cost for this process is around LKR 120,000.00 per annum for each distribution transformer.

The automatic load balancer is a shunt connected current injecting inverter. As well as current harmonics are becoming a considerable issues in the distribution sector and finding economically viable solutions for that. Active harmonic filters are one of the best solutions identified for harmonic mitigation. The automatic load balancer can be developed to fulfill the purpose of harmonic mitigation as active harmonic filter by changing algorithms in addition to the distribution load balancing.

6.2 Cost of the Equipment

Table 7 : Detail Cost of Equipment

No	Item	Description	QTY	Unit price (LKR)	Amount (LKR)
1	**IGBT**	1200V 150A	3	9000.00	27000.00
2	**Capacitor**	150uF 350VAC	3	2500.00	7500.00
3	**Capacitor**	1000uF 400V	2	750.00	1500.00
4	**Reactors**	4mH	3	2500.00	7500.00
5	**Gate drivers kit**	UCC21520	1	1500.00	1500.00
6	**Protection kit**	Amplifiers AMC 1311 AMC 1301 OPA 320	1	1200.00	1200.00
7	**Main Controller**	AT91SAM3X8E(ARDUINO DUE)	1	8000.00	8000.00

8	**Power supply**	650V 16V 12V 5V 3.3V	1	10000.00	10000.00
9	**CT**	100:5	6	2500.00	15000.00
10	**Connector bar**	100A	3	700.00	2100.00
11	**MCB**	100A	1	8500.00	8500.00
12	**Lugs**	25sqmm	30	180.00	5400.00
13	**Cu Cable**	25sqmm	7	900.00	6300.00
14	**outdoor enclosure**		1	12000.00	12000.00
15	**Assembler cost**		1	15000.00	15000.00
16	**Other accessories**		1	10000.00	10000.00
17	**Contingencies**		1	25000.00	25000.00
Total					163500.00

Price Sources: www.farnell.com, www.Digikey.com, Silverstone, Unitech and local market

6.3 Other Benefits

This same equipment can be used for harmonic mitigation with changing algorithms Sri Lankan electricity network consist of distribution control centers in the provincial level at present, but there is no monitoring system to distribution substation and its loading patterns. The proposed equipment can easily communicate with Distribution Control Center through the communication protocols and the detail profile of the distribution load patterns, and its key indicators can be monitored. Furthermore, Distribution controlling center can control the distribution feeder and substation by remote operation. Through this process, it can easily reach to the smart networking concepts by this equipment.

Previously collected data samples of Pannipitiya Feeder 07 indicated that the variations and behavior of load patterns at peak, day and off-peak durations.

Maximum load currents were recorded in night peak and it expands up to four hours as usual. As per the distribution transformer loading standard, the distribution transformer capable to load an additional 10% for four hours and 25% for one hour. Due to that, the distribution substation can be loaded up to 110% at normal conditions. But at present, transformer de-loading process is started when the load of the distribution transformer reaches to 75% of rated current in accordance to instructions provided in the distribution instruction and guidelines for balancing the loads. When the transformer load is balanced by using above proposed equipment, the load of the distribution transformer can be loaded up to 100% while keeping additional 10% for emergency situation. The gain of additional loading of 25% provides an opportunity for the congested areas and load centers. The enhance utilization of distribution transformers due to load balancing is an attractive benefit to distribution network and the economy of the country.

6.4 Simple Economic Analysis

Design and manufacturing Cost (LKR) = 163500.00

Saving of Quantified items per year(LKR)

1. Transformer Copper lost due to unbalance =25000.00
2. Cost of manual load balancing =120000.00

Total Saving (LKR) = 145000.00

Saving of non quantified items

1. Increases in transformer Life
2. Value of harmonic mitigation
3. Value of increases in power quality
4. Increase in capacity utilization
5. Remote monitoring and controlling facility
6. Overloading protection of distribution transformer

According to the above figures, simple payback period is less than two years.

7 CONCLUSION

Existing manual load balancing technique that practiced in the electricity distribution sector in Sri Lanka is not a sustainable solution. Since electricity consumption pattern and its variations cannot be estimated accurately due to the uncertainty in the use of modern heavy loads, solar generations, and loads due to weather changes.

The Automatic Load Balancer presented in this study is capable of balancing unbalanced current flow in distribution substations. This equipment was designed to handle up to 100A current per phase in both directions of injection and draw. The load current balancing is carried out at the low voltage terminals of the transformers such that the correction is valid for the entire upstream currents as well.

The Automatic load balancer can be installed at any identified location where unbalances exist either due to unbalanced customer loads or single-phase based solar generation.

This automatic load balancer algorithm can also be modified to for current harmonic mitigation as an active harmonic filter.

The designed automatic load balancer is an economically viable solution and the simple payback period is less than two years.

8 FURTHER DEVELOPMENTS

The designed automatic load balancer in this research is a bi-directional inverter of AC/DC/AC converter. This is connected to the distribution feeders ~~to~~ near the substation as shunt inverter. This equipment specification and switching arrangement is designed to use for multiple requirements to get more benefits from the same equipment.

8.1 Can be developed for Current Harmonic Mitigation

The power quality is another significant issue faced by the distribution engineers and also a reason to increase distribution losses. Within the next few years' distribution engineers have to face bigger challenges due to current harmonics. The best solution for current harmonic mitigation is an active harmonic filtering. The proposed automatic load balancer can be used as active harmonic filter by changing its algorithms.

Using this inverter and connection method it can easily be used for current harmonic mitigation without changing any hardware.

8.2 Can be used to Detect Overcurrent, Earth Fault Situation

Present LV distribution networks haven't proper mechanisms to detect over current and earth fault situations. The designed automatic load balancer can detect overcurrent and earth fault situations and can communicate the situation.

8.3 Remote Monitoring and Control Capabilities

Smart electricity network is one of the major focuses that discussed in all over the world. But this is something far away from present technology used in Sri Lanka. At present, there is no provision to monitor load pattern of a distribution substation and haven't facility to access and control distribution feeders and substation through remote operation.

Automatic Load balancer can be able to monitor load pattern and access the distribution feeders. Distribution Control Center that established in provincial levels can remotely trouble shoot through this equipment.

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