On-Line Automatic Switching of Consumers' Connections for Improved Performance of A Distribution feeder

O. Popoola, A. Jimoh, *Member IEEE and* D. Nicolae, *Member IEEE*

Abstract--**Resolving imbalances on phases is performed using conventional trial and error approach which involves service interruption. Phase current and voltage may improve however the resultant effect does not last for too long. To improve the performance of the secondary distribution system there is a need for an on-line and automating technology. The aim of this paper is to pioneer a method and technology for resolving imbalances in a secondary distribution system as a result of the uneven distribution of single phase load across a three phase power system. The technology developed involves monitoring, acquisition/display of collected data and self changing switching actions electronically for rearrangement or transfer of consumer loads. The proposed switching technology is based on open-transition switch that enables transfer or rearrangement of consumer loads in a three-phase system within milliseconds with supervisory control system. Validation of the proposed technology was carried out using these methodologies: Matlab (Simulink), Virtual Instrumentation-Lab VIEW and Hardware implementation.**

Index Terms-- **Automated technology, Distribution, Current imbalances, Load balancing, Phase arrangement, Phase voltage, Service interruption and Static transfer switching.**

I. INTRODUCTION

Ubalance is a frequently encountered issue in the distribution network especially in three phase power system that supply large single phase loads. This is as a result of subjection to load variations which might be due to load growth and the delay/non response to the need for construction of new substations and feeders within the system. Other maladies associated with the distribution systems include poor voltage regulation; peak power/energy losses; conductor heating/equipment damages; voltage and current imbalances being a major factor; [1, 2]. For instance South Africa's main electricity supplier, Eskom, is currently facing challenges concerning the supply of electricity during peak times, especially during the evening peak period (from 18h00 to 20h00). This is due to the electricity consumption in South Africa growing currently at approximately 1000 MW per annum. In the past, electricity demand in South Africa was addressed by the erection of large (3000 – 3600 MW) pulverized coal-fired power stations. The South African government currently has a goal to provide at least every household with electricity. This is proving to be successful, as there has been an overall increase in the electrified households from 50 % in 1995, to 69 % in 2003 [3]. This therefore may have contributed to frequent unbalance issue, power losses and etc on the distribution network that supply large single phase user in the country

Different methods have been proposed, researched, and presented for improvement of distribution network reconfiguration; these were mainly on the primary distribution system [1, 2, 3, 4, 5, and 6].

The distribution network is normally instituted at the primary side or medium voltage level of distribution network; however it has little or no significant influence on the problem created at the secondary side or the low voltage levels. Unbalance in the secondary distribution network increases the severity of the problems of voltage drop, power losses and large current in the neutral wire [7, 8].

Normally, to attain load balancing on phases, a conventional trial and error approach is used to maintain unbalance within the statutory level. This involves field measurements and the application of one's judgment. For example, to reduce the degree of the phase current unbalance in a feeder, the connection phases (load distribution points) need to be changed often to achieve phase balance after many field measurements and judgments analysis. With this approach service interruption is unavoidable; hence the rearrangement of consumers' load distribution points on phases cannot be performed frequently so that a level of service supply can be maintained to the consumers. Although using this approach, the phase voltage and current unbalances might improve, however the resultant change usually does not last for a long period of time [9]. Although Adisa, Siti & Davidson presented a method [10] that will assist one's judgment in the conventional trial and error approach thereby reducing service interruptions. However this is still insufficient taking into consideration the time-varying characteristic of load especially in the Southern Africa region.

Hence, the need for newer technological options in substation distribution systems in terms of monitoring and control which will ensure increased market service value in terms of adequate quality and reliability, reduce cost of operation and service interruptions.

This solution (technique) in the form of automation implementation using artificial intelligence, telecommunication and power electronics equipments in

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power systems will be to ensure continuous dynamic load balancing along the low voltage secondary feeder thereby relieving overload in the three-phase system or feeder with minimal service interruption; and reduce real power losses.

A method and technology for implementation, intended for improving the performance of the low voltage distribution feeder is addressed by this paper.

II. PROBLEM DESCRIPTION

Majority of the consumers at the secondary distribution are single phase loads. Often times these single phases are arranged or grouped to have a balanced three phase systems, however, unbalance still occurs due to unequal (unevenly) load distribution among the phases of the feeder. Resolving this issue so as to maintain balance within the statutory level requires a great deal of time apart from the time varying characteristic of consumer loads. This balancing status (2) usually lasts only a short time, such as one season, one month, one day or even only one hour.

Hence the need to evolve an automating technology to minimize the unbalance by transferring loads from the heavily loaded to less loaded phases so as to reduce power losses, voltage drop and etc.

Mathematically, the total power loss can be expressed as follows:

$$P_{loss} = \sum_{i=1}^{n} r_i \frac{P_i^2 + Q_i^2}{|V_i|^2} \tag{1}$$

And the voltage drop can be expressed as follows:

$$V_{drop} = |V_s| - |V_L| \tag{2}$$

The resistance, real power, reactive power, voltage of branch i, source voltage and load voltage are respectively $r_i, P_i, Q_i, V_i, V_s, V_l$; while n is the total number of branches in the system.

Although conventional trial and error approach is used for improving load balancing on the secondary level to minimize power losses, voltage drop and etc, the duration of the effects of the balancing varies from one distribution feeder to another due to the single phase loads that continually change across the three-phase feeder [6, 7]. Achieve

The main aim of this study is to propose an automation method and technology for minimizing unbalances in the feeders at the secondary distribution network. This is with a view to accomplish the following : ensure continuous dynamic on-line load rearrangement with minimal service interruption; rearrangement of consumer loads among phases; eliminate or reduce trial and error methods and guarantee that unbalance is within the statutory limit as shown in (3).

$$VUF = \frac{V_{mean} - Max(V_{ab}, V_{bc}, V_{ca})}{V_{mean}} \leq \%_{Limit} \tag{3}$$

Where $V_{mean} = V_{ab}, V_{bc}, V_{ca}$
V_{ab}, V_{bc}, V_{ca} are the line to line voltages

A. Phase and Load Balancing

Generally in South Africa, a distribution feeder is usually a three-phase, four wire system. It can be radial or open loop structure. The size of the conductor ($70mm^2$) for the entire line (about 200m) of the feeder is the same. These feeders consist of mixture of residential, commercial, and industrial loads. Single-phase loads are fed by single-phase two-wire service line ($16mm^2$,30m), while three-phase loads are fed by three-phase four wire ($3\phi 4$) service. The behavior of the daily load pattern is a function of time (time of use) and the type of customers.

The resulting power system voltages and currents at the distribution end and the points of utilization can be unbalanced due to several reasons. These reasons include the following: unequal voltages magnitude at the fundamental system frequency (under voltage and over voltages); fundamental phase angle deviation; asymmetrical transformer winding impedances, and etc [7]. However, a predominant cause of this unbalance is uneven distribution of single-phase loads as they continually change across a three-phase power system with use. Usually the load consumption of consumers connected to a feeder fluctuates, thus leading to the fluctuation of the total load connected to each phase of the feeder. This in turn implies that the degree of unbalance keeps varying. The worse the degree of unbalance the higher the power loss and the voltage drop, and the less reliable the feeder becomes.

To balance the phase currents in every segment and reduce the neutral line current is a very difficult task for the distribution engineers considering the fact that they do not have control over the utilization by the consumers. Trial and error approach is based on expert knowledge and judgment which involves the analysis of variety of interrelated meter indications to detect abnormal conditions such as circuit overloads, improper line voltages, etc. Other factors required in the exercise include the knowledge of voltage regulations, load flow analysis and minimization of circuit losses; use of mathematics to calculate resistive and reactive loads and phase relationship to identify unbalanced low efficiency load, circulating currents and undesirable conditions.

With the correct technology to provide the required input information most of these activities can be programmed to be performed by a dedicated microcontroller or processing unit.

III. PROPOSED TECHNIQUE

The key operational activities identified in the development of a technology for rearrangement of consumers load to minimize unbalance in a low voltage distribution system includes monitoring and acquisition of data; processing and communication of signal and data; control and switch transfer.

These activities can be achieved by separate functional units namely: (1) the switching unit and (2) sensing unit which together with the supervisory control station forms the intelligent unit package for the proposed technology. The block diagram in Fig. 1&2 shows the interaction of the functional units of the proposed technique and a typical scheme layout of a consumers' connection to a Feeder.

To assist in the knowledge of performance capabilities, operation features, and integration of functions of the intelligent unit package a practical and economic reality, a detailed design (illustrated by a block diagram) of the proposed technology is shown in Fig. 3.

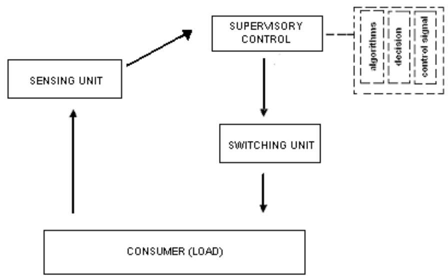

Fig 1: Proposed System Block Diagram

The package consists of the following main components:

- Switching device: Made of three phase ac static switch and operating mechanism that is capable of opening and closing the switching device remotely (complex digital signal processing).

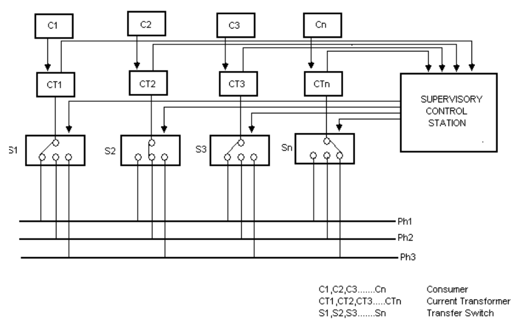

Fig 2: Typical model layout scheme of the proposed system

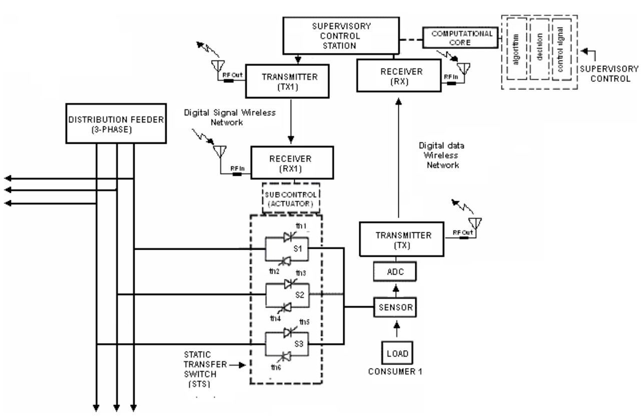

Fig 3: Schematic diagram of the proposed Technology

- Sensing unit: This unit depending on the problem formulation and solution technique or algorithm, which may be current or any other quantity at the consumer's connection node is required for monitoring of the system conditions; collection of input data; conversion of analogue sensor signal into digital data that can be recognized by microcontroller; and communication with the supervisory control station.
- Supervisory Control unit: consists of embedded microcontrollers for effective co-ordination, computational and control of other intelligent units.
- Communication unit: a means of data communication between the switching unit, sensing unit and the supervisory control station.
- And lastly, a common uninterruptible power supply unit capable of powering all components of the package.

The fundamental concept of the proposed technology is based on the open-transition switch that enables the transfer or rearrangement of consumer loads in the three-phase feeder system within milliseconds. This is made possible through supervisory control system for effective co-ordination, computational and control of other intelligent units.

A. *Construction of the proposed technology*

Starting with the switching unit as shown in Fig. 3, this comprises mainly the static transfer switches (STS) and the sub control. The static transfer switch is made of two pair of thyristor connected in inverse parallel for each phase. During normal operation one of the static transfer switches is in ON mode or close position (example S1) allowing the conduction of current to the load (consumer) while the other two pair of static transfer switches (S2 & S3) are in the OFF mode or open. When the rearrangement (transfer) operation is required due to overload on the current phase (example S1) being used, S2 or S3 is turned on to conduct the current to the load from the phase that can accommodate the existing consumer and balance (or minimize the unbalance) of the three phase feeder. Then the current in S1 is blocked at the first zero crossing. The control actions sent from the supervisory control (SC) is carried out through a logic switching circuit acting as the operating mechanism or better known as the actuator. The actuator is part of the sub control.

The sub control is interlinked with the SC and located on the line. It is designed to acquire data, switching status and transfer same to the SC through a communication interface (wireless link) and also perform switching action. The monitored information (from the sensing unit design) and the command (control) signal to switches S1 or S2 or S3 to perform a transfer operation from Phase 1 (Red) to Phase 2 (Blue) or Phase 3 (Yellow) when the preferred source voltage or current deviates from the pre-set upper or lower limit is sent from the SC via the sub control.

B. *Operating and Control Scheme*

As shown in Fig. 3 and Fig. 4, voltage sensing device continually monitored the voltages on each of the phases while current transducer monitored the current on the phase on which the load is connected.

The monitored information is transmitted from the sensing unit via wireless communication to the SC station where decisions are taking based on the solution algorithms. These decisions are in relation to the problem of finding a condition of balancing as expressed mathematically by Siti et al. (2005) using current system for a random point of connection "k" in a network with 3 phases and shown in the (4), (5) and (6).

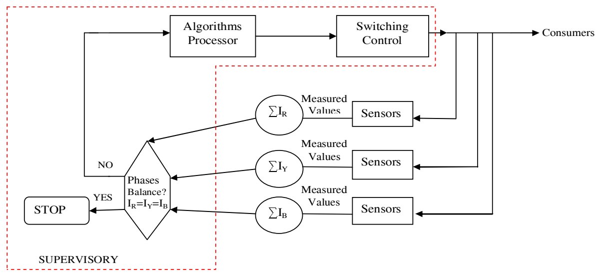

Fig 4: Flow process of the proposed system

$$I_{ph1k} = \sum_{i=1}^{3} sw_{ki} I_k + I_{ph1(k-1)} \tag{4}$$

$$I_{ph2k} = \sum_{i=1}^{3} sw_{ki} I_k + I_{ph2(k-1)} \tag{5}$$

$$I_{ph3k} = \sum_{i=1}^{3} sw_{ki} I_k + I_{ph3(k-1)} \tag{6}$$

where, I_{ph1k}, I_{ph2k} and I_{ph3k} represent the currents (phasors) per phase (1, 2 & 3) after the k point of connection; $sw_{k11} \ldots sw_{k33}$ are different switches; while I_{k1}, I_{k2} and I_{k3} represent different load currents (phasors) connected to the distribution system at point k of connections.

In the case of unbalance, the SC sends the command signal to sub control (S_bC) of the switching unit for the static transfer switch (S1) of load I_k via wireless communication to open, while within a micro second a signal is sent to S2 or S3 of the same load I_k to close.

IV. SOFTWARE VALIDATION

The validation to test the operation and behaviour of the proposed technology was carried out using the Simulation and Virtual implementation methodologies.

A. *Simulation*

The operation of the proposed system was modeled using the MATLAB 6.5 version as shown in Fig. 5.

The simulation results shown in Fig. 6 and Fig. 7 below consists of three-phase source; a constant impedance load with a power factor of 1 and a source impedance. Ideal thyristor' were used for the design of the switching circuit. Parallel thyristor are used to increase the surge current rating of the ac switch (static).

i). Transfer during Voltage Unbalance.

Under normal conditions, static switch (S1) is turned on and current flows from the primary source to the load; when current unbalance is detected by the supervisory control; the gate signal is removed from S1. Since switch S1 has a higher voltage potential than ac switch S2, the gating signal of S2 must be held off until ac switch S1 naturally commutates (allowing finite time to elapse). The minimal transfer time, in this simulation, is between to 3-5 *ms* from the start of the unbalance due to high inductive load as shown in Fig. 6. The transfer time takes longer since the current zero crossing lags voltage zero crossing.

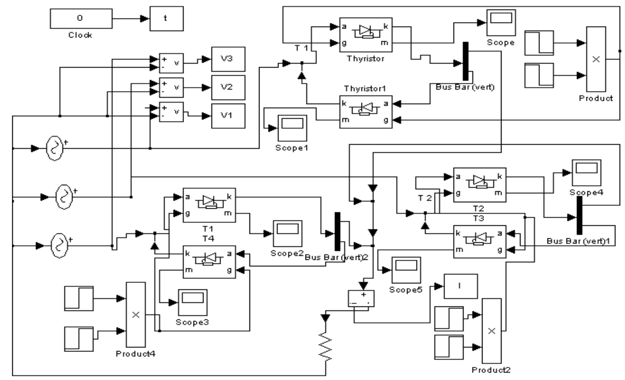

Fig 5: Simulation model design of the proposed scheme

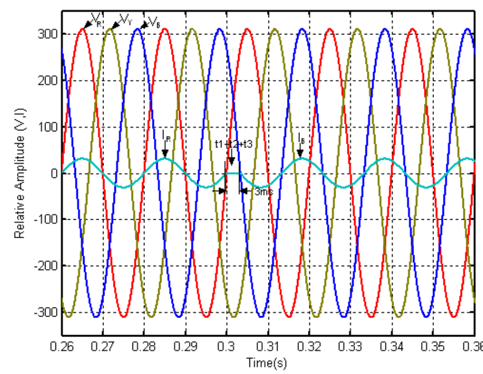

Fig 6: Current Transfer Operation

B. *Virtual Implementation*

In this section adaptive representation of the proposed technology and its multiple execution operation was simulated and studied in relation to the focus of this paper.

The virtual implementation was carried out using a Workstation-Intel Pentium CPU 1.90 GHz, 256 MB of RAM having a version of Lab View 7.0. The process control, as well as acquisition, processing, storing and reporting of all data, is achieved through the virtual instrument (VI).

For the distinct blocks, different virtual instruments were created using the block diagram approach in Fig. 7. The program with the functions in the virtual instrumentation are created and shown as module. The module is made of various subs VI; to facilitate and perform different operations; and communicate with other sub VI.

i. Module 1: VI for source supply.
ii. Module 2: VI for fundamental of AC circuit, monitoring of the system variables and part of the sensing unit.
iii. Module 3: VI for the switching operation (switching unit) of the proposed technique.
iv. Module 4: VI to monitor phase displacement and transfer.
v. Module 5: VI for Monitoring and Graphical display of the I-V characteristic in terms of unbalance.
vi. Module 6: VI for Synchronization of the Activities of the Proposed Technology.

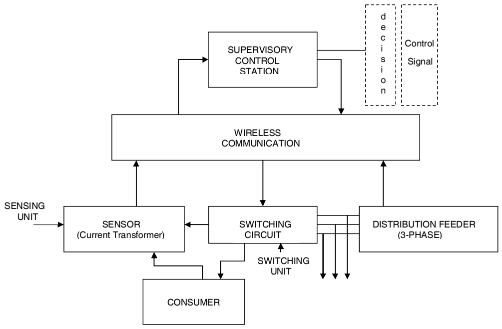

Fig 7: Block Diagram Outlining the Approach in Lab VIEW

VI block panel model of the proposed technology as shown in Fig. 8 was developed using the module outlined above.

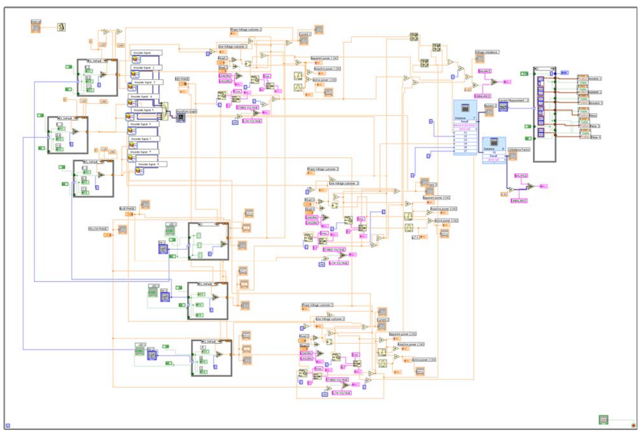

Fig 8: Proposed Technology for Optimal performance Block Panel

Different scenarios were carried out in order to verify the operational performance of the proposed technique as graphically and computational displayed in Fig. 9 & 10.

i) Test : Rearrangement of Consumers for Optimal Performance of a Three-Phase Feeder

Two unbalance scenarios as shown in Fig. 9 and 10 in a three phase feeder network were adopted for a model scheme.

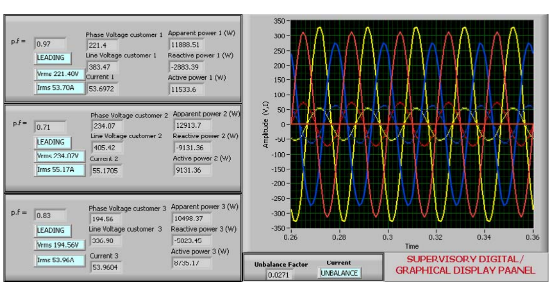

Fig 9: Unbalance scenario on the LV distribution feeder (3-Φ)

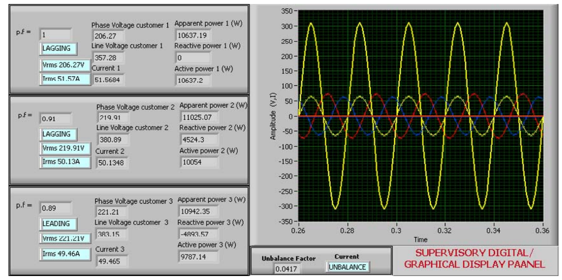

Fig 10: Unbalance scenario on LV feeder (uneven load distribution on a phase

Scenarios 1(Fig. 9) represents an unbalance state due to the uneven load distribution among the phases –Red, Yellow (White) and Blue continually changing. Scenario 2 (Fig.10) shows an unbalance scenario on the distribution feeder attributed to the resultant load distribution on a particular phase - the consumer loads (Z_{21}, Z_{22}, Z_{23}) on Yellow Phase which eventually affects the total load Z_2, Z_1, Z_3 of each phase thereby making the Feeder unbalance.

Signal plot of the phase voltage, the line voltage, the load current and the numerical data (values) of the electrical input and output parameters for each scenario are displayed on the computer screen as shown as shown. An initial sampling rate of 10 Hz at every 10 samples of data gave very sluggish signal plot response. This was stepped up during the test to a sampling rate of 1000Hz using 100 samples at a lag time of 100ms was use for logging data/test.

<u>Result & Observation</u>

Fig. 9 & 10 shows an unbalance scenario with a value of 0.027(2.7%) & 0.042(4.02%) which is greater than 2%. This is due to load values of Z_1, Z_2, Z_3 or Z_{21},Z_{21}, Z_{23}. Hence the need to rearrange the loads to achieve minimal unbalance.

Using the proposed technology as shown in Fig.11, Loads were arranged such that the resultant load on each phase is equal or approximate as shown in Fig. 11; the Consumer using switch 1 is switched to the BLUE phase from the RED phase, Consumer using switch 2 is still on the YELLOW phase as previous and Consumer using switch 3 is switched over to the RED phase.

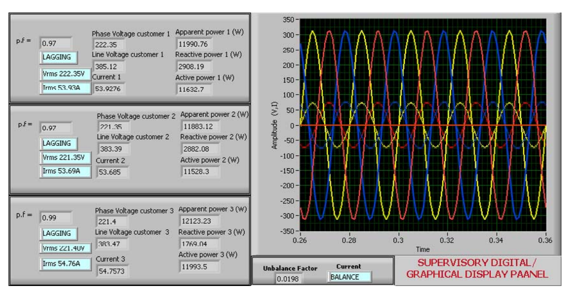

Fig 11: Change of Consumer Phases to achieve Balance on the Three Phase Feeder System (Blue, Yellow and Red)

Similar rearrangement was carried out for scenario 2 which eventually resulted in minimal unbalance in the three-phase Feeder as shown in Fig. 11. The Consumer load (Z_{21}) is transfer or changed from the Yellow Phase to another Phase (BLUE) which can accommodate the load to achieve minimal unbalance on the Feeder according to the statutory standard.

For the computation of the unbalance at the supervisory control, the ANSI definition of voltage unbalance expressed in terms of current unbalance was applied for operational and demonstrative purpose as shown in (7). Other standards can be applied.

$$\%\ \text{Current Unbalance} = \frac{3\left(I_{max} - I_{min}\right)}{I_R + I_Y + I_B} \times 100\% \qquad (7)$$

Where I_R, I_Y and I_B are the phase current of R, Y, B, I_{max} and I_{min} are the calculated maximal and minimal phase currents.

Conclusion

From the different scenarios, the transfer of consumer within the phases was accomplished within millisecond due to automation of the switching device, while computational function was able to show the state of the feeder at any point in time in both numerical value and plot forms at a glance.

C. Experimental Implementation

Schematic diagram in Fig. 12 was used for hardware implementation of the switching unit of the proposed technology. The test was performed with and without the safety device using a variable three phase power supply at 220 V rms; incandescent lamp of 100 W 230 V as load; a rotary switch for change of phase. A Tektronics 2000 series Digital oscilloscope 4 Channels as the test facility.

i). Hardware Result

The real time voltage and current waveforms of the test circuit (Fig.12) is shown in Fig.13. The three - phase voltage supply is shown by the waveform in Light Blue, Red and Dark Blue. Each having a peak value between 290 and 311V as shown by a division of 10 V representing 100V on the y-axis; the resultant $V_{rms} \approx$ 205 V – 220 V. The phase displacement is ±120°. The magnitude of the current (I_{rms}) is $\approx$ 0.455 A – 0.5A or peak value of 0.65 A as shown by the green sinusoidal waveform. The output shows that there are some transient's effects as a result of the use of the triac.

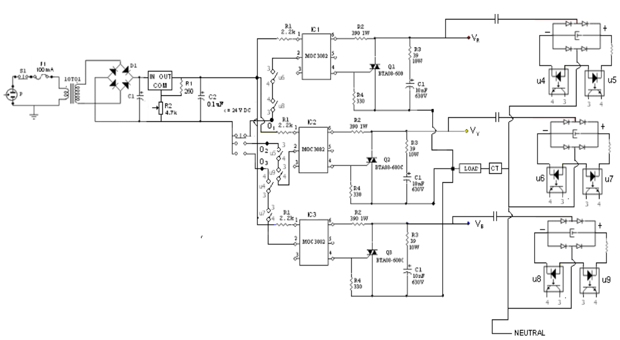

Fig 12: Schematic diagram incorporating the Safety device

ii). Transfer Operation of the switching unit

The transfer time shown in Fig. 13 was more than the 5ms. This is due to the use of a rotary switch taking into consideration the commutation time of the switch (triac). This time can be considerably reduced using an automatic or remote control device to at least 5 ms as depicted in Fig. 6. As shown in Fig. 13 and 14, the load current is in phase with the supply voltage when transfer operation takes place.

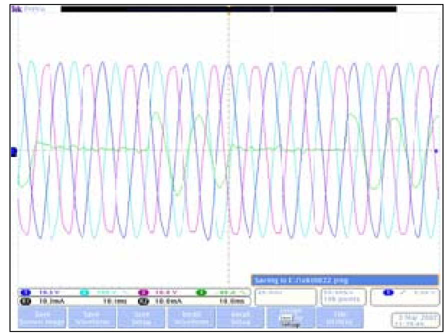

Fig 13**:** Transfer of Load from one Phase to another Phase

The transient (low tungsten resistivity) generated or transmitted from the ac source (load circuit) did not affect the signal circuits as demonstrated by the transfer operation waveform in Fig.14.

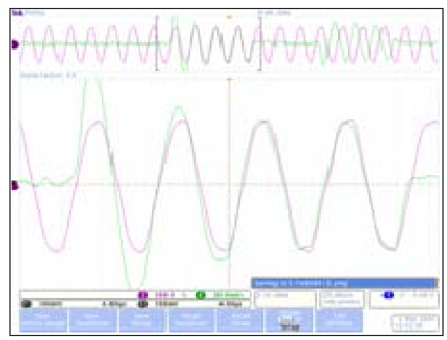

Fig 14: Surge current as a result of load being connected.

This was as a result of the opto-coupler MOC 3084 that has the capability of being use with static transfer switch in the interface of logic system or control with equipment power from low voltage ac source. Although there was considerable time for the switch to naturally commutates, there is a need to integrate a safety device for the protection of the customer both in terms of individual and equipment; the distribution system and its operational personnel; as well as the proposed technology. To achieve that, a safety device was introduced in the form of two Opto-isolator switches (exp. u4 and u5; u6 and u7; u8 and u9) having their dc supply from the source supply of each phase connected as shown in Fig. 12.

Under normal conditions, assuming S1 is turned on (u4 and u5 in normal closed position (NC)) and current flows from the primary source to the load. When unbalance is detected, S1 is turned OFF by removal of the gate signal; S2 receives a gate signal to start conduction to accommodate the load. Assuming S1 is still turned ON due to the commutation time, u5 and u9 (S2 switch) will remain in the open position until the commutation process is achieved before closing. At no time will there be the possibility of two phases being in the ON mode at anytime. The resulting waveform to depict the operation has been shown in Fig. 13.

V. FINAL CONCLUSION

The research focused on the need to evolve a technology for minimizing unbalance thereby enhancing the performance of the Feeders in the secondary distribution network. The problem of phase current and voltage imbalances due to uneven distribution of loads in a secondary system feeder has been address by the proposed technique.

The idea of using automatic and remote technology based on the open-transition switching concept has been implemented with great success and shown to be realizable as shown from the results obtained and deduced in the course of the further work carried out such as:

- Rearrangement of consumers can be carried out among the phases (results obtained in Figs. 6, 11, and 13).
- Less time could be used in resolving unbalance instead of reliance on physical measurement and application of the personnel judgment (trial and error approach).

The main aim of this study has been accomplished. Among other contributions of this research which were established and accomplished using the technique includes continuous dynamic on-line load rearrangement with minimal service interruptions; reduce power losses and voltage drops. This technology will be technically advantageous as well as economical for the utilities and the customers, in terms of the variable costs reduction and better service quality respectively.

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