On-Line Remote and Automatic Switching of Consumers' Connection for Optimal Performance of A Distribution Feeder

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

Abstract--**Load balancing on phases is performed using a conventional trial and error approach. With this approach, service interruption is unavoidable; hence rearrangement of consumers load distribution points on phases cannot be performed frequently. Also phase voltage and current imbalances might improve using this approach but the change does last for too long. To get the secondary distribution to operate at its optimal performance, a technique in the form of remote and automated technology is needed. This paper contributes such a technology at the low voltage side of the distribution network. The proposed static transfer switching technology is based on the open-transition switch that enables transfer or arrangement of consumer loads in a three-phase system within milliseconds and supervisory control system for effective co-ordination, computational and control of other intelligent units.**

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

I. INTRODUCTION

THREE-phase voltage unbalance is a frequently encountered issue in secondary (LV) distribution network and in primary (MV) distribution power system that supply large single phase loads. Although different methods were proposed, researched, and presented for improvement of distribution network reconfiguration, these were mainly on the primary distribution system [1, 2, 3, 4]. Since distribution network is normally instituted at the primary side, or medium voltage level of distribution network, it has little or no significant influence on the problem created at the secondary side, or the low voltage levels. Although, most often technically these single-phase loads are arranged such that the 3-phase system is balanced; the fact, however, is that 100% balanced operation all the time is impossible. At best what happens is that the unbalanced is maintained within a statutory level. Unbalance in the secondary distribution network increases the severity of the problems of voltage drop, power losses and large current in the neutral wire [5, 6].

Traditionally, to achieve load balancing on phases, a conventional trial and error approach is used. 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 the phase voltage and current unbalances might improve using this approach, the change usually does not last for a long period of time [7].

Adisa, Siti & Davidson presented a method [8] 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.

To ensure increased market service value in terms of adequate quality and reliability, reduce cost of operation and service interruptions, there is a need for an optimal solution or technique. This technique 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.

This technique in the form of automation implementation using artificial intelligence, telecommunication and power electronics equipments in power systems will be an optimal solution that is technically advantageous as well as economical for the utilities and the customers, in terms of the variable costs reduction and better service quality respectively.

As noted above, solution and approaches proposed in all previous papers were designed to deal with feeder reconfiguration from the standpoint of mostly feeder loss reduction and load balancing. These mostly addressed the mathematical formulation and definition of the problems; and proffering solution methodologies; but with little emphases on the method of implementations and the technology for implementation.

This paper, however, addresses a method and technology for implementation, in order to reduce unbalance to a minimal level at the low voltage distribution network.

II. PROBLEM DESCRIPTION

Current researches have shown that, modifying the radial structure of the primary feeders from time to time by changing the on/off status of the sectionalizing and tie switches to

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transfer loads from one feeder to another, may significantly improve the operating conditions of the overall system. This, however, usually has no significant effect on the secondary side of the distribution network, especially its reliability.

Majority of the consumers load at the secondary distribution are single phases. In as much as these single phases are arranged such that the three-phase system is balanced, unbalanced still occurs due to the unequal (unevenly) load distribution among the phases of the feeder. Hence the need 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:

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

And the voltage drop can be expressed as follows:

$$V_{drop} = |V_s| - |V_L| \quad (2)$$

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 [1, 2].

The main aim of this study is to research and propose a method and technology for automatically minimizing the unbalances in the secondary distribution network feeders with the view to achieve the following:

- Rearrangement of consumers loads among the phases uniformly so as to achieve load balance at the secondary distribution level.
- To eliminate or reduce trial and error (manual operations) methods.
- Evolve techniques or system for ensuring continuous dynamic on-line load rearrangement with minimal service interruption; and reduced power losses, and voltage drop.
- Ensure that unbalance is within the specified limit.

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

where V_{mean} =Mean of V_{ab}, V_{bc}, V_{ca}

V_{ab}, V_{bc}, V_{ca} are the line to line voltages

A. Phase and Load Balancing

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 (3ϕ 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 [5]. A predominant cause of this unbalance, however, is uneven distribution of single-phase loads as they continually change across a three-phase power system with use. Normally 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 (manual method) 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

In developing technique for rearrangement of consumer load to minimize unbalance in a low voltage distribution system there is a need to identify the key areas of operation of the proposed technology. These are the switching unit and the sensing unit which together with the supervisory control station forms the intelligent unit package.

A block diagram of the proposed technology is shown in Fig.1.

The package consists of the following main components:

- Switching device: Made of three phase ac static switch as well as operating mechanism (actuator-control unit) that is capable of opening and closing the switching device remotely (complex digital signal processing), even during a load unbalance or system outage.

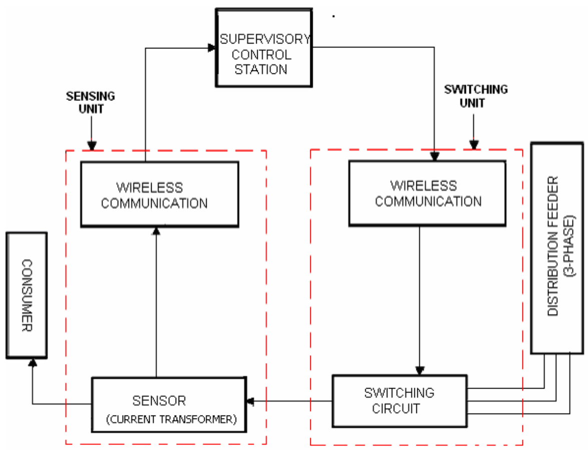

Fig. 1 Block diagram of the proposed system

- 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 may be required.

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.

The proposed technology is designed to monitor and detect unbalance due to uneven distribution of load among the phases, and consequently transfer load from the heavily loaded phase to the lightly loaded ones to achieve optimal balance condition. A typical layout of consumer connections with respect to the proposed system is as shown in Fig. 2

A. Construction of the proposed technology

Starting with the switching unit, which 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

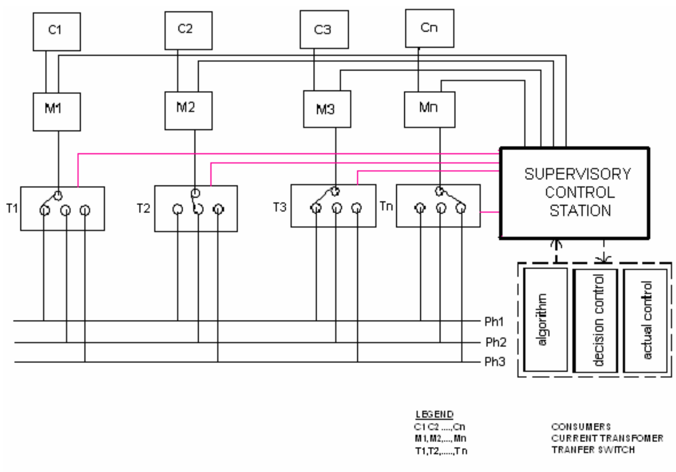

Fig. 2 Typical layout of consumer connections to a feeder system

Construction of the proposed technology (contd)

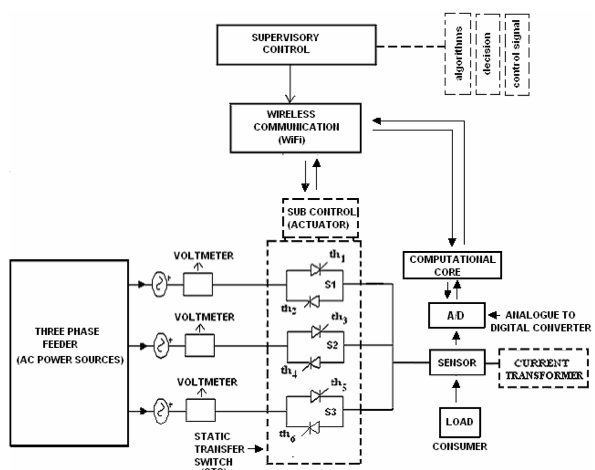

Fig. 3 Schematic diagram of the proposed Technology

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 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 supervisory control and located on the line. It is designed to acquire data, switching status and transfer same to the supervisory control through a communication interface (wireless link) and also perform switching action. The monitored information 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 supervisory control via the sub control.

The monitored information (real time data) is realized through the sensing unit design whose functional modules include: the sensing interface which is made of the sensor and analogue digital converter; computational core; and communication medium for transfer of data to the supervisory control station.

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 (using) wireless communication to the supervisory control station where decisions are taking based on the solution algorithms.

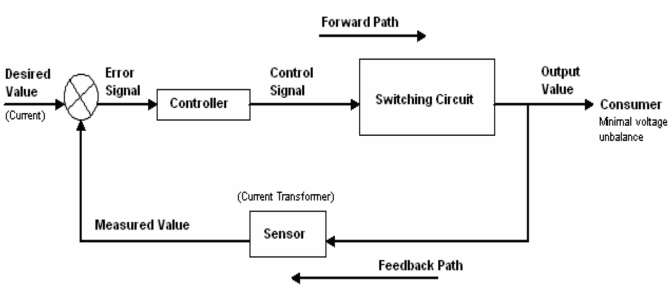

Fig. 4 Closed loop operation of the proposed system

These decisions is in relation to the problem of finding a condition of balancing as mathematically expressed by Siti *et al.* [2] using a network with 3 phases and shown in the equations below

$$I_{ph1k} = \sum_{i=1}^{3} sw_{k1i} I_{ki} + I_{ph1(k-1)} \quad (4)$$

$$I_{ph2k} = \sum_{i=1}^{3} sw_{k2i} I_{ki} + I_{ph2(k-1)} \quad (5)$$

$$I_{ph3k} = \sum_{i=1}^{3} sw_{k3i} I_{ki} + I_{ph3(k-1)} \quad (6)$$

where, $I_{ph1k,} I_{ph2k}$ and I_{ph3k} represent the currents (phasors) per phase (1, 2 & 3) after the k point of connection; $sw_{k11} ... sw_{k33}$ 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.

The SC sends the command signal to sub control of the switching unit for the static transfer switch (S1) via wireless communication to open, while within a micro second a signal is sent to S2 or S3 to close when the prefer load current on phase 1 deviates from the pre-set upper or lower limit (IU or IL) of the following conditions:

1. The phase-angle difference of the phases is within the pre-set value.
2. The voltage of the alternate source is within the limit.
3. The alternate phase or phases can accommodate the required load.

The status of the static transfer switches is also communicated back to the supervisory control station.

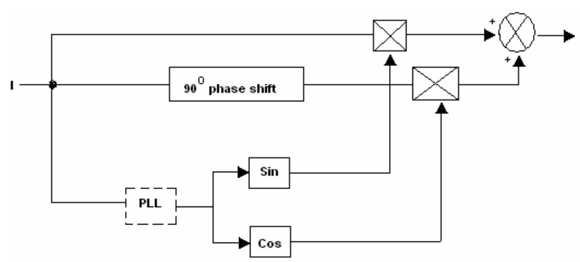

Fig. 5 Block diagram of current sensing

Figure 5 shows a block diagram of the current sensing. The current transformer measures or detects the value i which is proportional to the amplitude of the source current on the phase in use (Phase).

The phase current, $I = i \sin\theta$ is previously phase-shifted by 90^0 and $i \cos\theta$ is obtained.

Then i is calculated using equation (7)

$$i = i \sin\theta \times \sin\theta + i \cos\theta \times \cos\theta \quad (7)$$

where the phase θ is derived from the phase locked loop (PLL) if synchronized to the phase current. The current sensing is able to response instantaneously to a current unbalance because it detects the current amplitude as a dc value without any time delay unlike in case of using smoothing filter.

IV. SIMULATION RESULTS

The operation of the proposed system was modeled using the MATLAB 6.5 version. The simulation 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 designed of the switching circuit. Parallel thyristor are used to increase the surge current rating of the ac switch (static switch).

A. 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.

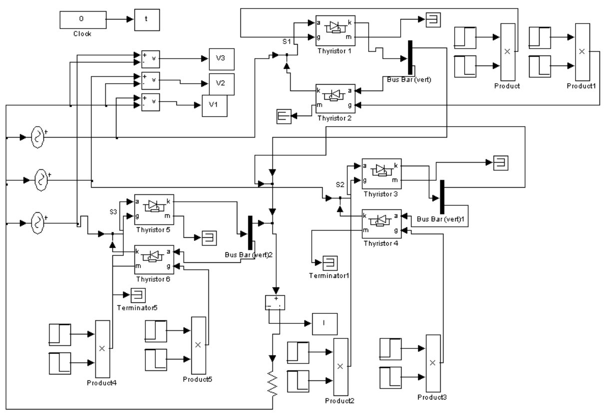

Fig. 6 Simulation model design of the proposed scheme

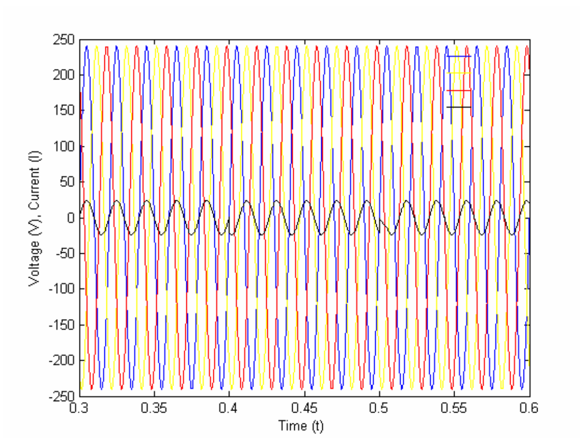

Fig. 7 Simulation result of the proposed scheme

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 transfer time, in this simulation, is close to *5 ms* from the start of the unbalance due to high inductive load as shown in Fig. 8. The transfer time takes longer since the current zero crossing lags voltage zero crossing.

V. CONCLUSION

A technique for an on-line remote and automatic switching and rearrangement of consumer connection for optimal performance of a secondary distribution network feeder has been presented. The proposed scheme addresses the problems of phase current and voltage imbalances due to uneven distribution of loads in a secondary distribution system feeder. The system utilizes static transfer power electronics switching devices, which has proven to be a very effective tool in solving unbalances in the low voltage distribution network.

The system is practically realizable, although only its operating characteristics have been demonstrated here through a Matlab simulation. This is a report of an on-going work. The full practical details of the proposed scheme is hoped to be reported in the subsequent paper when the work is completed.

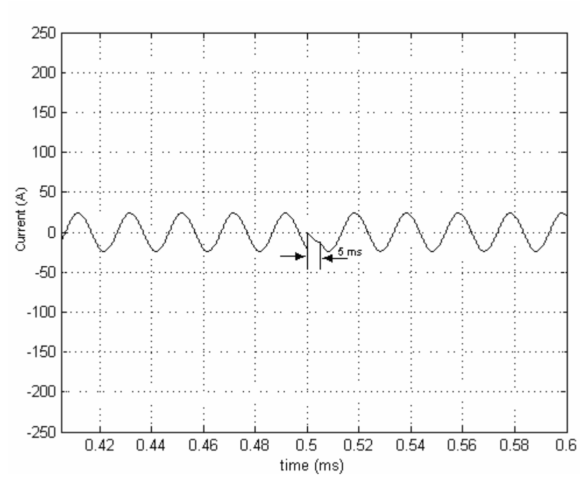

Fig. 8 Test Results of transfer operation

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