



DESIGN AND IMPLEMENTATION OF A BALANCED THREE-PHASE POWER PROTECTION SYSTEM

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Manuscript Received: 15/11/2019 Accepted: 12/12/2019 Published: December, 2020

ABSTRACT

This work considers the design and implementation of a balanced three-phase power protection system used to load sharing formula at consumer receiving end to ensure uniform distribution of the available three-phase voltage supply-source. Various methods have been developed with the main objective to provide an engineering solution to the effects causing unbalanced three-phase voltage supply. The engineering solution considered in this research work was designed and implemented with the use of local raw materials in Nigeria. This solution is thus achieved by employing voltage-tap changing technique at both primary and secondary sides of the three-phase transformer. The transformer is auto-winding star connected type where its star point is taken as system design-neutral point. However, whether the unbalanced voltage is due to an unbalanced single phase loading or unstable network supply within the plant, this system can continuously correct and adjust the correction level as required to $\pm 0.4\%$ of the set nominal voltage, and zero the voltage imbalances to give out 100% balanced voltage.

Keywords: *Three phases, power supply, reliability, balanced voltage.*

INTRODUCTION

For many reasons bothering on imbalance, unequal voltage values (and currents) does occur on three-phase circuits in a power distribution system. Perfectly balanced circuits are not possible in the real world (Sti, Jimoh, and Nichole, 2017). Power quality issues are seen in all electrical networks in different degrees and frequencies, while short sags and surges are common, networks can have voltage supply irregularities that are constantly present on the network, or may last for a long period (Shahnia, Wolfs, and Ghosh, 2014).

Essentially, the resulting current imbalance is caused not only by the system voltage disparity but also by the nature of the loads causing imbalance - heating and cooling loads, and single phase motors are connected in such a way that a single-phase conductor carries more amount of current than the other two that is, compared to the other two phases, the Line to Neutral Voltage of one phase is lower. Likewise, one Line to Neutral Voltage is higher than the other two, where most of the load is connected over just two phases. However, in both cases, Line to Line voltages are affected. Single phasing, which is the complete loss of a phase, is the ultimate voltage unbalance condition for a three-phase circuit. Unbalanced voltages can cause serious problems, particularly to motors and other inductive devices. However, perfectly balanced systems are often assumed, such that a value of 415/220V would be measured at each output phase conductor from the output of the supply transformer. Typically, these voltages may differ by a few volts or more. It is when voltages differ excessively that problems occur. Unbalanced voltages occur because of variations in the load and fault in the system. When the load on one or more of the phases is different from the other(s), unbalanced voltages will appear.

Providing a lasting solution to this problem has become a major engineering challenge, as well as a major concern to consumers who are at the receiving end of the troubling effect of phase imbalance. Most industrial load at three phases need

balanced three phase supply, and when this is not available or in short supply especially in quality, they pose danger to the efficient working of the industrial machine. To solve voltage three phase unbalance problem, (Sti, Jimoh, and Nichole, 2017) developed an algorithm that automatically performs load adjustment function thereby reducing the three-phase unbalanced rate. The authors in (Shahnia, Wolfs, and Ghosh, 2014) proposed the genetic algorithm with voltage imbalance and penalty factor as the objective function. In contrast, this paper proffer a solution to the problem of unbalance voltages by converting single phase supply to a three-phase balanced supply. Electronic control systems are the foundation of modern, efficient industrial processes. The reliability and performance of instruments, actuators, sensors, programmable logic controllers (PLC) and relays can all be affected by the quality of power supplied to them. It is very important to proffer engineering solutions for implementation to improve reliability and to ensure a balanced three phase voltage supply. This research will contribute to the improvement of three-phase power supply imbalance not only in the laboratory equipment but also in other equipment placement. The outcomes to be considered include:

1. The improvement in the supply system itself.
2. Development of a new approach to remove voltage imbalance.
3. Standard enhancement of percentage voltage imbalance.

The Balanced Three-phase Power Protection System ensures a continuous, regulated supply of utility voltage, where the electrical infrastructure is stressed, unstable or unreliable. This research provides a fast, accurate voltage regulation that secures voltage productivity by improving consistency in operations and eliminates the impact of fluctuating current on equipment and production. Also, this research ensures a regulated supply of voltage, helping to streamline operations and optimize resources to reduce wasted capacity and improve the return on operational investment. Fig.1. below shows the system details.

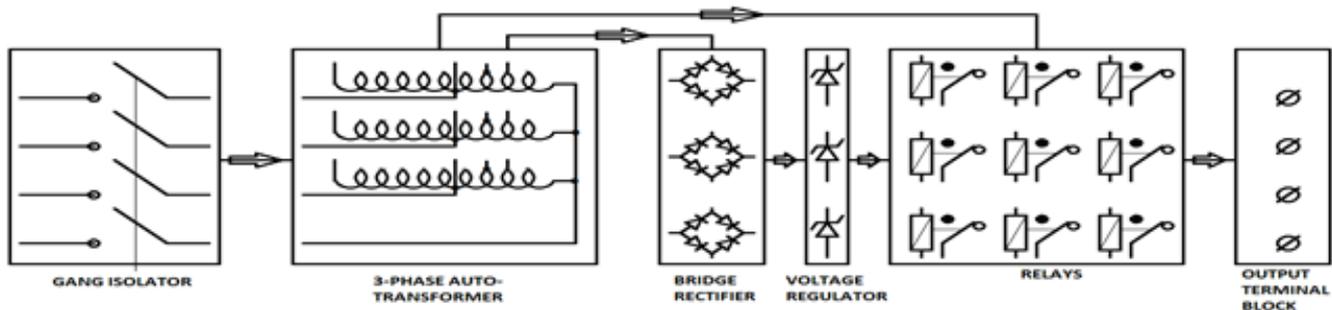


Fig.1: System block diagram

MATERIAL AND METHODS

This research is a three-phase type, comprising of the power circuit and control circuit; designed for use in environments where an unstable network or utility voltage affects productivity. The information

presented in this paper is intended as a primer on unbalanced voltages that affect electric motors.

Power Supply Unit:

This section consists of heavy power side of the system and it basically runs from input voltage mains

to the load input via output contactors or relays, as shown in Fig.2. The input voltage mains considered for this project design ranges from 229V to 231V phase voltage. In terms of line voltage, it is $229 \times \sqrt{3} = 396.6V$ to $231 \times \sqrt{3} = 400.1V$.

Hence, it is fed into the primary winding of auto-voltage transformer windings at a tapping point shown in Fig.2. Also, inclusive, is the transformer-less power supply circuit taking care of under voltage and over-voltage relay indications (Christopherson, 2018).

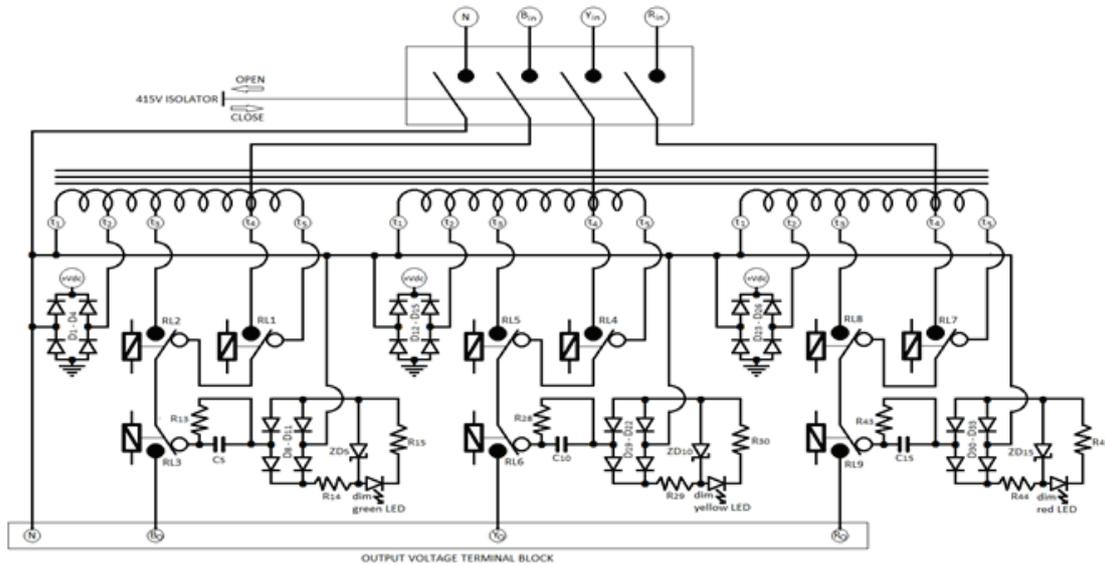


Fig.2: System power circuit

Control circuit / Regulation Stage:

In this design, an automatic voltage regulator (AVR) is used to correct under-voltage and overvoltage, as well as voltage unbalance. As an active device, the AVR automatically compensates for all voltage fluctuations, provided that the input voltage to the AVR is within its range of magnitude and speed of adjustment. Protective relay employed in this control circuit can detect single phasing, phase voltage imbalance and reversal of supply phase rotation. Overall, it protects equipment from the degrading effects of imbalance. Also, phase sequence under voltage and overvoltage relays are connected in the control circuit shown in Fig.3. (Gosbell, Perera, and Smith, 2000), and (Mckenzie, 1995).

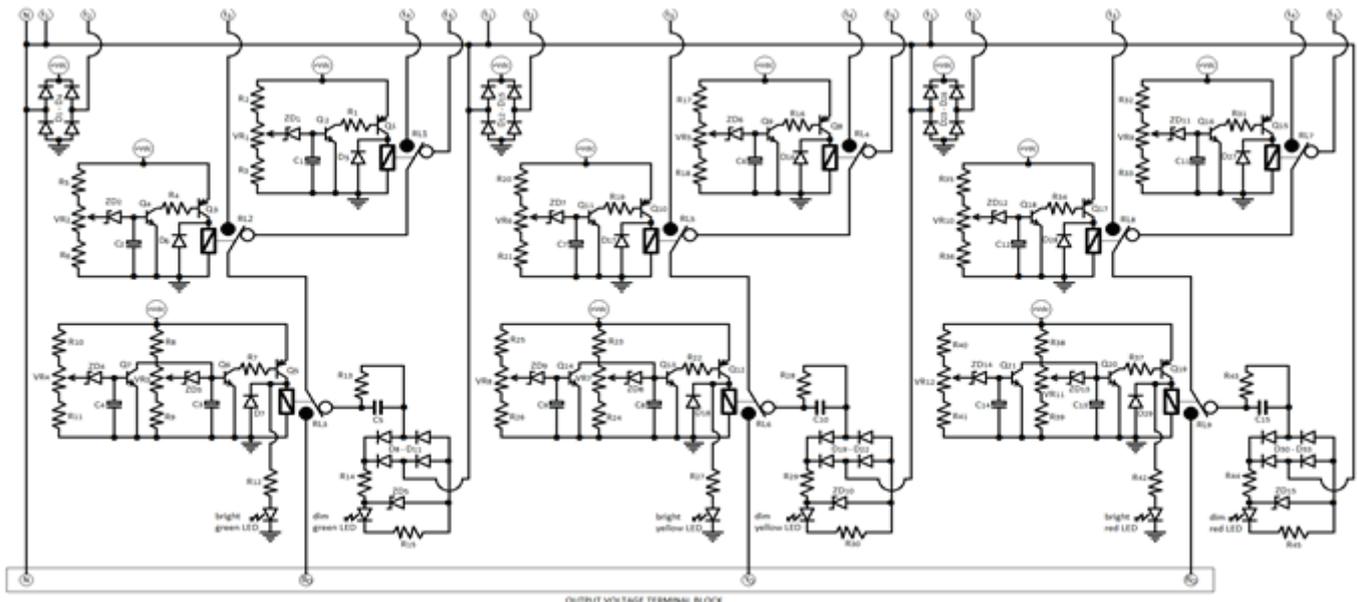


Fig. 3: The system control circuit

Operation of the System

A 415V gang isolator is switched ON to the three-phase supply and neutral to energize 1.2KVA three-phase auto-star connected voltage transformer. If the input voltage to the transformer is within the range of 396.2V and 399.6V, 398V will be received at the output voltage block terminal, via the relay contacts.

RESULTS AND DISCUSSION

System Circuit Analysis

1.2KVA three-phase auto-star connected voltage transformer receives supply via 8 poles-single throws, 4-gang isolator switch. The type of voltage transformer considered for this research is 3-phase, 3-leg core-type transformer; consisting of windings R, Y, B.

For easy analysis, winding B is taken as a single-

phase entity for reference, which is a replica of the other two windings. Winding B is auto-transformer winding, containing the number of taps which is five (5). It is either step-down or stepped up as the primary voltage varies between 229V and 231V. There are t1, t2, t3, t4 and t5, where t1 – t5 represents tapping points. The tap position t1 is taken as neutral terminal.

Tap position t2 is the secondary voltage terminal ranging from 12.52V to 12.63V, rectified by diodes D1 – D4 structured as bridge rectifier providing dc supply to the control circuit as shown in Fig.3. The tap position t3 is also another secondary voltage terminal, stepped down to 230Vac when primary voltage attains a value of 231Vac.

Tap position t4 is serving two purpose, first, it is the primary voltage terminal of the winding, and second, it is a secondary voltage terminal for desired voltage 230Vac whenever primary voltage attains a value of 230Vac.

The tap position t5 is a secondary voltage terminal, stepped up to 230Vac when primary voltage attains 229Vac.

Accordingly, in Fig.3, relay RL1-normally closed contact is connected to winding terminal t5 when primary voltage assumes 229Vac. However, when the primary voltage shoots up to 230Vac, transistor Q1 is turned ON, making RL1 to be energized and the normally open contact of RL1 is connected to winding terminal t4 as indicated in Fig.3; as a result of potential divider arrangement in the control circuit in which action of R2, R3 and variable resistor (preset) VR1 that provide 0.6V or more above Zener diode voltage of ZD1 to push transistor Q2 into conduction mode, and this will clamp the base of Q1 to ground via resistor R1 through the collector and emitter of Q2.

Nonetheless, when the primary voltage increases to 231Vac, the potential divider arrangement of R5, R6 and VR2 will provide 0.6V or more above Zener diode voltage of ZD2, and at the same time make transistor Q4 to conduct, and this will clamp the base of Q3 to ground via resistor R4 through the collector and emitter of Q4.

Transistor Q3 will now conduct since its base is at a negative potential as compared to its emitter, while relay RL2 will be energized to connect its normally open contact as shown in Fig.3. RL3 normally open contact is closed and supply is finally received at the output voltage block terminal (Bo) 230Vac with respect to the neutral N.

If and only if the input voltage drops below 229Vac, RL3 will be de-energized while supply will be interrupted to the output voltage terminal block and dim green LED will light up via the transformer-less circuit.

However, if primary voltage rises above the set range by the present value of VR4, there is going to be Zener diode voltage of 0.6V and above at the base of Q7 turning it ON, while the base of Q6 is connected

to the ground via the collector of Q7 and through its emitter giving rise to Q5 turning OFF and RL3 being de-energized; hence, supply will be interrupted to the output voltage terminal block, and the dim green LED will light up; this action is known as overvoltage protection (Salivahanan, Suresh, and Vallavaraj, 2000).

IMPLEMENTATION

A 2 X 2 gang, 6 pole-single throw change-over switches were reconstructed by merging together and transformed to 1 X 4 gang, 8 pole-single throw isolators of 415V voltage rating. The winding of the transformer was constructed on sectional bases of single-phase winding which is auto-winding. Windings R, Y, and B were finally star connected by joining taps t1 of phase windings R, Y and B, giving rise to three-phase auto-star connected voltage transformer. Also, the transformer was constructed using insulated copper wire as winding on bobbins for windings R, Y and B of an equal number of turns and taps respectively. It was ensured that all windings were enclosed by E-shaped/laminated iron sheet, structured as three-phase, three-leg core-type voltage transformer, as shown in Fig.4. Control circuits were constructed using electronic components of equal values, but different potentiometer settings along with relays RL1 to RL9.

The voltage dividers were so arranged in the control circuits to provide 0.6V or more above Zener diode voltage to the following transistors into conduction: Q2, Q4, Q6, and Q7. Emitter, base and collector pins of all transistors were fixed into Ferro board, while diodes and electrolytic capacitors connected considering their polarities as required by this design. Soldering process played an important role in this construction by employing soldering lead and iron; the whole construction was packaged on the project board of dimension 29.5cm X 53cm X 3cm



Fig. 4: Three-phase, three-leg, core-type voltage transformer.



Fig. 5: Component arrangement

EVALUATION AND OUTCOME

Testing of the project was carried out with the aid of multi-meter. Three phase voltage supply was applied to the primary side of the auto-transformer and output voltages are shown as tabulated (in table 1) and graphically in Fig. 6 below.

Table 1. Values of V_1 and $V(t_2)$

TABLE OF VALUES					
VOLTS	READINGS				
V_1	228.5	229	230	231	231.5
$V(t_2)$	12.49	12.52	12.57	12.63	12.65

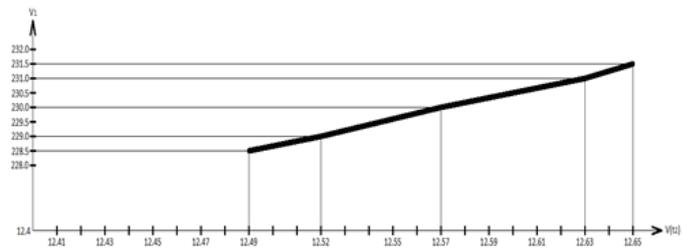


Fig.6: Graph of input voltage (V_1) against control circuit voltage (V_{t_2})

Fig. 6 shows the graph of input voltage against control circuit voltage. As can be seen in the graph, as the input voltage increases, there is a corresponding increase in the control circuit voltage. The increase in the control circuit voltage controls the switching action of the relay to ensure the required balanced voltage out is obtained.

Table 2. Values of V_1 and V_o

TABLE OF VALUES					
VOLTS	READINGS				
V_1	228.5	229	230	231	231.5
$V_{o/p}$	$V(t_{3,o/p})$	$V(t_3)$	$V(t_4)$	$V(t_5)$	$V(t_{5,o/p})$
	229.5	230	230	230	230.5

Fig. 7: Graph of output voltage (V_o) against input voltage (V_1)

Fig. 7 shows the graph of output voltage against input voltage. As can be seen in the graph, as the input voltage increases, there is a corresponding increase in the output voltage up to a certain point where a continuous balanced output voltage is observed. This implies that, if an increase in the input circuit voltage is experienced, the system regulates its output voltage to ensure the supply of a balanced output voltage. By calculation, the following outcomes confirm readings obtained from AVO-meter:

From $V(t_2) = [N(t_2) / N_1] \times V_1$

Where $N(t_2) = 82$ turns, $N_1 = 1500$ turns and V_1 ranges 228.5 to 231.5volts.

For $V_1 = 228.5V$, $V(t_2) = [82/1500] \times 228.5 = 12.49V$

For $V_1 = 229.0V$, $V(t_2) = [82/1500] \times 229.0 = 12.52V$

For $V_1 = 230.0V$, $V(t_2) = [82/1500] \times 230.0 = 12.57V$

For $V_1 = 231.0V$, $V(t_2) = [82/1500] \times 231.0 = 12.63V$

For $V_1 = 231.5V$, $V(t_2) = [82/1500] \times 231.5 = 12.65V$.

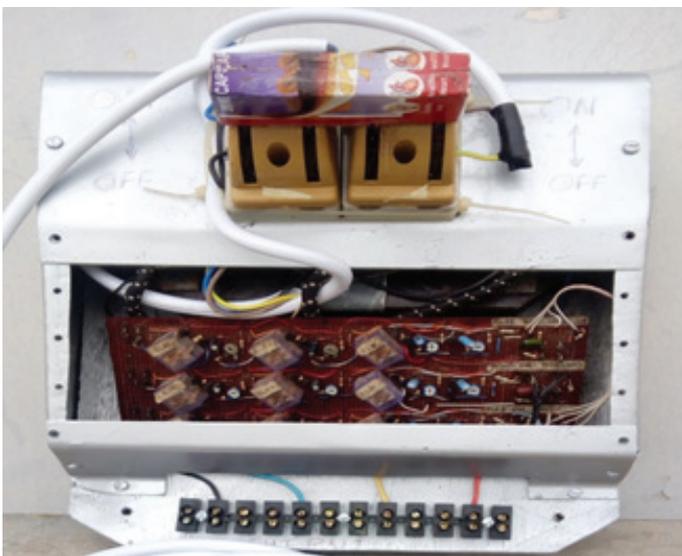


Fig.6: System package

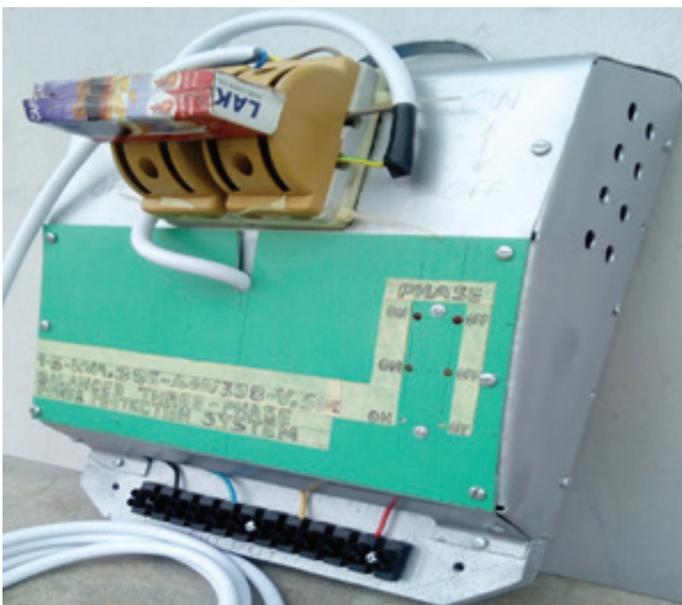


Fig.7: System package showing side view

Also, from $V_t = [N_t / N_1] \times V_1$

N_t ranges from $N(t_{3o})$ to $N(t_{5o/p})$ where $N(t_{3o/p}) = N(t_3) = 1494$ turns, $N(t_4) = 1500$ turns and $N(t_5) = N(t_{5o/p}) = 1507$ turns.

$N_1 = 1500$ turns, V_1 ranges 228.5 to 231.5volts.

For $N(t_{3o}) = 1494$ turns and $V_1 = 228.5V$, $V(t_{3o}) = [N(t_{3o/p}) / N_1] \times V_1 = [1494 / 1500] \times 228.5 = 229.5V$.

For $N(t_3) = 1494$ turns and $V_1 = 229.0V$, $V(t_3) = [N(t_3) / N_1] \times V_1 = [1494 / 1500] \times 229.0 = 230.0V$.

For $N(t_4) = 1500$ turns and $V_1 = 230.0V$, $V(t_4) = [N(t_4) / N_1] \times V_1 = [1500 / 1500] \times 230.0 = 230.0V$.

For $N(t_5) = 1507$ turns and $V_1 = 231.0V$, $V(t_5) = [N(t_5) / N_1] \times V_1 = [1507 / 1500] \times 231.0 = 230.0V$.

For $N(t_{5o/p}) = 1507$ turns and $V_1 = 231.5V$, $V(t_{5o/p}) = [N(t_{5o/p}) / N_1] \times V_1 = [1507 / 1500] \times 231.5 = 230.5V$.

$V(t_{3o/p})$ is the voltage at the minimum cut off point, while $V(t_{5o/p})$ is that voltage at the maximum cut off point.

However, it has been established that $V(t_3)$, $V(t_4)$ and $V(t_5)$ represent V_o of the constant voltage value of 230Vac.

Testing for unbalanced three-phase voltages:

This could be better done by taking sample voltages from the input to the three-phase auto-star connected voltage transformer, as shown in Table 3:

Table 3. The measured line to line voltages showing unbalanced quantity.

INPUT VOLTAGES		
Measured Line-to-Line Voltage	L_1-L_2	396V
	L_2-L_3	398V
	L_3-L_1	400V
Voltage Sum		1194V

From (Gosbell, Perera, and Smith, 2002),

$$\text{Average Voltage} = \frac{\text{Voltage Sum}}{\text{Number of occurrence of line - to - line voltages}} \dots\dots\dots(1)$$

$$= 1194 / 3 = 398V$$

Maximum Voltage Deviation from Average Voltage = $398 - 396 = 2V$

Percentage Voltage imbalance = $100 \times (2/398) = 0.5 \%$

Testing for balanced three-phase voltages:

The first step in testing for balanced three-phase voltages is to measure line-to-line voltages at the output voltage block terminals, which is $230 \times \sqrt{3} = 398V$. Current in each supply phase is equally measured when the load is finally connected.

Calculation on temperature rise:

The voltage imbalance can also increase the current imbalance and promote a temperature rise that is much greater than the voltage imbalance percentage.

Unbalance voltage can be defined as (Gosbell, Perera, and Smith, 2002):

Percentage Voltage Imbalance = $\frac{= 100 \times (\text{Maximum Voltage Deviation from Average Voltage})}{(\text{Average Voltage})} \dots\dots(2)$

However, with perfectly balanced voltages arrived at in this design, branch circuit voltages on 398/230V is exactly 230V measured at each output phase conductor at the supply transformer, as shown in the table below:

TABLE 4. The measured line to line voltages showing balanced quantity.

OUTPUT VOLTAGES		
Measured Line-to-Line Voltage	L_1-L_2	398V
	L_2-L_3	398V
	L_3-L_1	398V
Voltage Sum		1194V

Illustrating the above formula; using equation (1) with line-to-line voltages of 398V, 398V, and 398V.

Average Voltage = $(\text{Voltage Sum}) / (\text{Number of occurrence of line-to-line voltages})$
 $= 1194 / 3 = 398V$

Maximum Voltage Deviation from Average Voltage = $398 - 398 = 0V$

Percentage Voltage imbalance = $100 \times (0/419) = 0\%$

Temperature Rise % = $2 \times (\text{Voltage Imbalance } \%)^2 \times 100$

*From Table 5, the Temperature Rise % can be calculated as thus:

Temperature Rise % = $2 \times (0)^2 \times 100 = 0\%$.

However, studies demonstrate that with every 10° of temperature increase, the average life expectancy of insulation is reduced by 50%. Table 5. Present percentage voltage imbalance and percentage temperature rise

TABLE 5: Percentage voltage imbalance and temperature rise

% VOLTAGE IMBALANCE	% TEMPERATURE RISE
1%	2%
1.7%	5.78%
2%	8%
2.15%	9.25%
3%	18%
4%	32%
5%	50%

Transformer rating:

Current $I = 3A$, Voltage $V = 398V$, frequency $f = 50Hz$ and power factor $P.f = \text{Cos } \theta = 0.8$

From active power $P = IV\sqrt{3} \text{ Cos } \theta$ (Mckenzie, 1995), (Pillay, Hofmann, and Manyage, 2002).

$P = 3 \times 398 \times 0.8 \times \sqrt{3} = 1.7Kw$

From apparent power = $IV\sqrt{3} = 3 \times 398 \times \sqrt{3} = 2.1KVA$.

CONCLUSION

Voltage imbalance and its negative relationship to motors and other electrical equipment is quite complex, and information presented in this paper is intended to correct this anomaly and to ensure a zero percent imbalance.

However, whether the unbalanced voltage is due to an unbalanced single phase loading or unstable network supply within the plant, this system can continuously correct and adjust the correction level as required to $\pm 0.4\%$ of the set nominal voltage, and zero the voltage imbalances and give out 100% balanced voltage. Since single-phase loads are switched unpredictably or distributed unevenly which is the major cause of line voltage imbalance, it could be recommended that the project designed and developed in this paper has been specifically to provide a continuous balanced voltage at the utility supply level.

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