VOLTAGE BALANCING IN LOW VOLTAGE DISTRIBUTION NETWORKS USING SCOTT TRANSFORNERS

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ABSTRACT

A low voltage (LV) radial feeder balancing method using Scott transformers is introduced in the paper. It converts an unbalanced three-phase voltage into a balanced three-phase voltage at either a downstream location on the feeder or at a three-phase load supply point. A "small scale" physical voltage balancing system using the proposed method is established and tested on an LV feeder in the laboratory. Test results demonstrate that the system maintains a balanced 3Φ voltage by compensating for voltage rises and voltage drops caused by single phase load variations.

INTRODUCTION

To help the transition to a low carbon economy, the UK government has announced numerous targets to accelerate the deployment of renewable micro-generation and energy saving technologies. In addition, grants and incentives have been established to encourage the purchase of low carbon devices and support the associated research and demonstration projects, e.g. Renewable Heat Incentive (RHI) Scheme for heat pumps and Low Carbon Vehicle Procurement Program (LCVPP) for electric vehicles (EVs). The net effect will be a reduction in energy consumption, but increased electricity demand as urban transportation moves to EVs and electricity powered heat pumps reduces our dependency on natural gas [1]. In addition, these devices will affect power quality in low voltage (LV) networks (400V in Europe), increase the occurrences of phase voltages moving outside acceptable statutory limits and boost the peak coincident electricity demands [2].

Small-scale DGs (SSDGs) connected to an LV feeder could provide power to a local community and because of their proximity to the loads, and tendency to use sustainable sources of primary energy, the carbon emissions will be significantly reduced as compared to a conventional power system with bulk fossil fuelled generators. However, SSDGs would alter the power flow direction and deteriorate the power quality. In addition, the single-phase nature of many LV connected EVs, heat pumps and DGs results in worsening problems of voltage unbalance especially on LV 3Φ, 4-wire radial feeders.

Voltage unbalance has an adverse effect on the LV protection and control systems. Protection coordination or grading becomes more problematic and may result in the mal-operation of relays. In addition, the current that flows in the neutral, caused by phase voltage unbalance, risks overheating the neutral and affecting the power quality seen by loads at the remote ends of an LV feeder. Voltage unbalance is usually expressed using the voltage unbalance factor (VUF), which is defined as

$$\mathrm{VUF\%} = \left|\frac{V_-}{V_+}\right| \times 100$$

where V_- and V_+ are the negative and positive sequence voltage components, respectively. The IEC standard limits VUF to 2% in LV networks [3] and the Engineering Recommendation P29 states that VUF should be kept within 1.3%, although short term deviations (less than 1 minute) may be allowed up to 2%.

Owing to the flexibility and fast response time of power electronic converters the power quality on a distribution system can be improved by the connection of DGs and energy storage or the use of UPS and STATCOMs [4]. Moreover, security, measurement and communication systems can be integrated to the converters. For voltage unbalance on the LV network, a power electronics based AC-DC-AC solution is viable, which first converts the unbalanced AC to DC, and then outputs a balanced three-phase AC voltage. However, because of the inherent nonlinearity associated with the switching operation, this solution would increase the presence of non-sinusoidal currents and voltages. Moreover, the conduction and switching losses occurring during the AC-DC-AC conversion would reduce the power delivery efficiency. In addition, the critical components in a converter have a shorter lifetime than traditional network components such as transformers; the switches are mostly IGBT-transistors having an average lifetime of ten years and capacitors often begin to fail after five years [5]. Moreover, the fault rate of these components varies significantly according to the operating conditions, which would further weaken the reliability of the converters.

This paper will introduce an LV radial feeder voltage balancing method using Scott transformers. Compared with the power electronics based AC-DC-AC solution, this one based on transformers and tap changers has a longer lifetime and does not inject harmonics into the LV network. A "small scale" physical voltage balancing system based on the proposed method is established and tested in laboratory to demonstrate the feasibility of the proposed method. The paper will describe the operating principles of the proposed balancing method, the design of the experimental plant and the test results obtained when the system was evaluated.

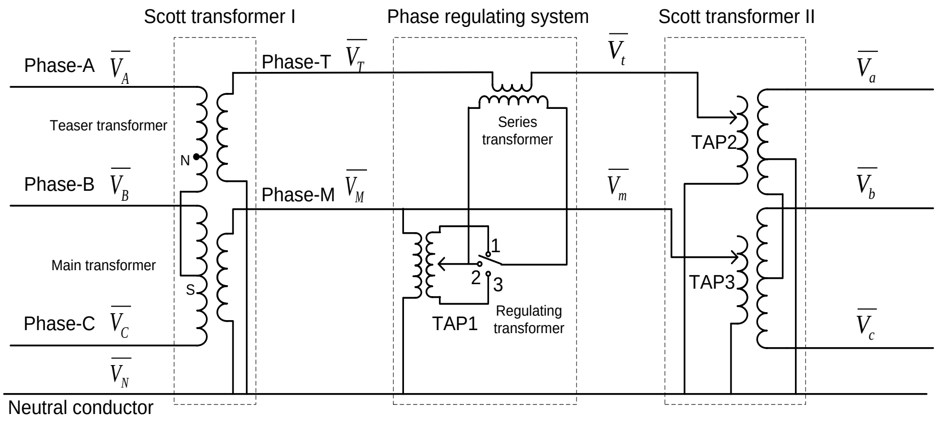

Fig. 1 The diagram of the proposed voltage balancing system

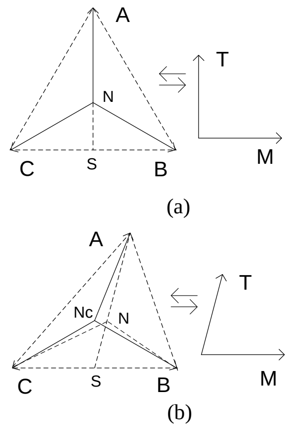

Fig. 2 Three- and two-phase voltage conversions

VOLTAGE BALANCING METHOD

The proposed voltage balancing method is able to convert an unbalanced 3Φ voltage into a balanced 3Φ voltage suitable for supplying the downstream loads on an LV feeder. The unbalanced 3Φ system is converted to an unbalanced two-phase system, and then restored to a balanced 3Φ system after the voltage regulation has been implemented on the 2Φ system. Fig. 1 shows a circuit diagram of the voltage balancing system, where the 2Φ system consists of phase-T and phase-M. Balancing is achieved in three parts: Scott transformer I, phase regulating system and Scott transformer II. Scott transformers are used for the conversions between the 2Φ and 3Φ systems and the phase regulating system is used to orthogonally balance the voltage phase angles of T and M, i.e. ensure the voltage phase difference is 90°.

Scott transformer

A Scott transformer is a 3Φ/2Φ connecting device, historically used to link two-phase and three-phase power systems with bi-directional power flow. As shown in fig. 1, a Scott transformer is made up of two single-phase transformers: a teaser transformer and a main transformer. The primary (three-phase side) of the teaser transformer has $\sqrt{3}/2$(86.7%) times the turns of the main transformer, and is connected to the primary midpoint S of the main transformer [6]. The point N on the teaser transformer is the neutral point of Scott transformer. The three phase voltages, imposed by the three phase conductors of the LV feeder with respect to N, have no zero sequence component.

The Scott transformer is able to convert a balanced 3Φ voltage to a balanced 2Φ voltage, and vice verse, as shown in fig. 2(a). However, if the supplied three- or two-phase voltage is unbalanced, the output voltage would be unbalanced as shown in fig. 2(b), where N indicates the neutral point on the Scott transformer and Nc indicates the neutral conductor. When a three phase voltage supply with a zero sequence component supplies a Scott transformer, there would be a voltage difference between N and Nc. In fig. 2(b), the three phase voltages NcA, NcB and NcC (Solid lines), having zero sequence component, is converted to an unbalanced two-phase voltage, whilst for the inverse conversion, this unbalanced two-phase voltage is converted to a three phase voltages NA, NB and NC, having no zero sequence component. The 3Φ-2Φ-3Φ system conversion, using Scott transformer, is able to eliminate the zero sequence component.

Scott transformer I in fig. 1 is used to convert the unbalanced 3Φ voltage ($\overline{V_A}, \overline{V_B}, \overline{V_C}$) to an unbalanced 2Φ voltage ($\overline{V_T}, \overline{V_M}$). Note: the Scott transformer I neutral point N is not connected to the neutral conductor due to the voltage difference between them.

Scott transformer II is used to convert the phase angle orthogonally balanced two-phase voltage ($\overline{V_t}, \overline{V_m}$) into a balanced three-phase voltage ($\overline{V_a}, \overline{V_b}, \overline{V_c}$). For this transformer, the neutral point N is connected to the neutral conductor. Tap changer TAP2 is added to the primary of the teaser transformer to control the amplitude of $\overline{V_a}$. Tap changer TAP3 is added to the primary of the main transformer to control of the amplitude of $\overline{V_b}$ and $\overline{V_c}$. According to the properties of Scott transformer, the amplitude equality of the output three phase voltages means that the three phase voltages are balanced.

Phase regulating system

The phase regulating system is applied to regulate the phase angles of the unbalanced two-phase voltage ($\overline{V_T}, \overline{V_M}$), so that the phase difference between the resultant two-phase voltage ($\overline{V_t}, \overline{V_m}$) is 90°. As portrayed in fig. 1, the phase regulating system is made up of a series transformer and a regulating transformer with tap changer TAP1. One end of the series transformer is connected to the regulating transformer through the tap changer and the other end through a single-pole three-throw switch.

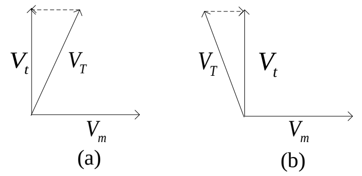

Fig. 3 Operations of the phase regulating system

When the phase difference between $\overline{V_T}$ and $\overline{V_m}$ is exactly 90°, the switch would connect to pin 2 in fig. 1, i.e. no voltage is injected in phase-T. Fig. 3 shows that when the phase difference between $\overline{V_T}$ and $\overline{V_m}$ is not 90°, the switch connects to pin 1 or pin 3 to inject a specified voltage into phase-T, so that the resultant $\overline{V_t}$ has a phase difference of 90° with $\overline{V_m}$. The amplitude of the injected voltage can be controlled by the tap changer TAP1.

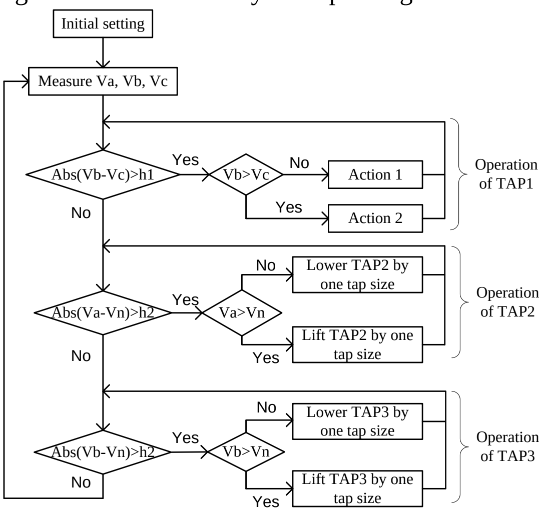

Fig. 4 The main control algorithm of the proposed method

Control algorithm

When Scott transformer II is supplied by an unbalanced two-phase voltage, it would output three phase voltages $\overline{V_a}, \overline{V_b}, \overline{V_c}$ as shown in fig. 1. The phase angle difference between phase-T and phase-M voltages can be obtained by comparing the amplitudes of $\overline{V_b}$ and $\overline{V_c}$: if $\overline{V_b}$ and $\overline{V_c}$ have the same amplitude, phase difference between the two phase voltages is 90°; if $\overline{V_b}$ is larger than $\overline{V_c}$, the phase difference would be larger than 90°; if $\overline{V_b}$ is smaller than $\overline{V_c}$, the phase difference would be smaller than 90°. The main control algorithm of the proposed method can be divided into three operations as portrayed in fig. 4, where, abs means the absolute value; h1 and h2 are the acceptable tolerances and Vn is the desirable output voltage amplitude. In fig. 4, action 1 refers to the phase difference increase associated operation and action 2 refers to the phase difference reduction associated operation. In this balancing method, only the output three phase voltage amplitudes are required to be measured.

LABORATORY TEST

Experimental plant

A "small scale" physical voltage balancing system based on the proposed method has been implemented in a laboratory using an existing 3Φ LV feeder. Fig. 5 shows the configuration of the experimental plant. The experimental plant starts from a 400V three-phase source, followed by isolation transformers and a three-phase variac. A 150m cable is used to draw power from the variac to supply three 40W bulbs. Along the cable, a 200W bulb is tapped on phase-A and a 60W bulb is tapped on phase-C. These two bulbs would induce an unbalanced 3Φ voltage for the downstream bulbs. The balancing system is located before the three 40W bulbs to provide them with a balanced three-phase voltage supply. The single-pole three-throw switch and all the tap changers are implemented using miniature relays. A control system based on a microcomputer is used to automatically control the switch and taps operating within the balancing system. Fig. 6 shows the configuration of the control system, where the microcomputer measures the 3Φ voltages using the analogue input circuit, and sends tripping signals to the relays to control the tap positions. The interfacing board is used to interface the microcomputer with the sensors, taps and switches in the balancing system.

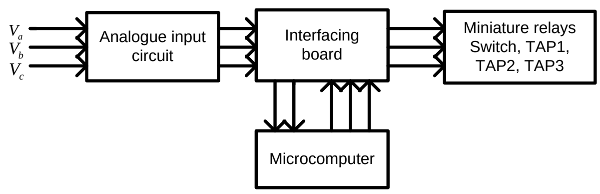

Fig. 6 The configuration of the control system

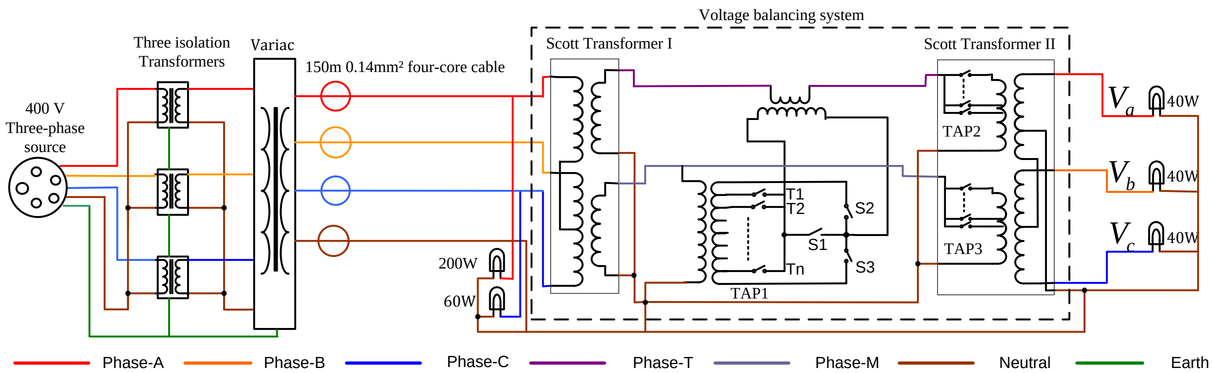

Fig. 5 The configuration of the experimental plant

Case studies

Case1: This case compares the three-phase voltage at the output of the balancing system before and after the system is started. As show in fig. 7, the balancing system is started at 0.63s and prior to this, the VUF is 9.52%. After approximately 200ms, the balancing system completes its operation and the VUF is reduced to 1.42%.

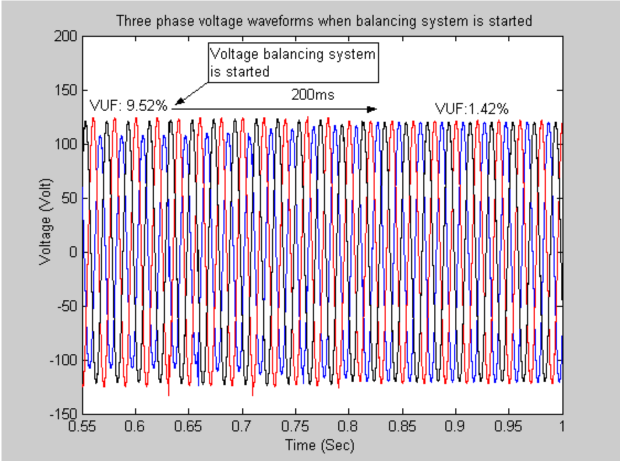

Fig. 7 Three-phase voltage when balancing system is started

Case 2: This case investigates the transient response of the balancing system to load reductions. As shown in fig. 8, the VUF is initially 1.2% with the balancing system in operation. At 0.88s, the 200W bulb on phase-A is disconnected, and the effect is a 10% phase-A voltage rise. After approximately 300ms, the balancing system completes its operation and the resultant VUF is 1.79%.

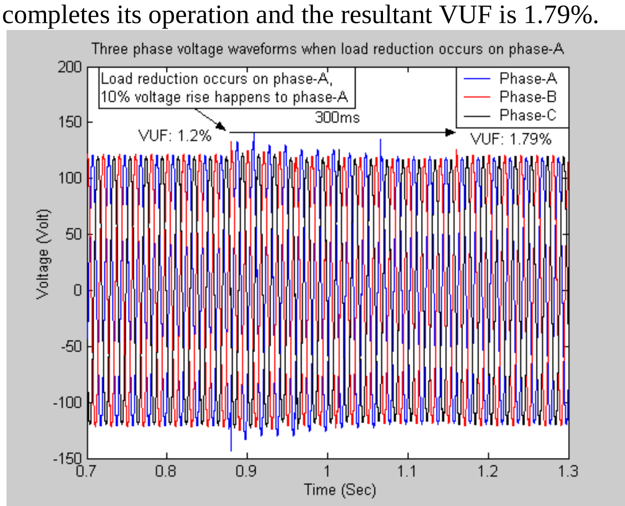

Fig. 8 Three-phase voltage when load reduction occurs on phase-A

Case 3: This case investigates the transient response of the balancing system to load increases. Initially, the 200W bulb on phase-A is disconnected and the VUF is 1.7% with the balancing system running as shown in fig. 9. At 0.77s, the 200W bulb is connected to phase-A and the phase voltage drops by 25%. In about 378ms, the balancing system completes its operation and the resultant VUF is 1.21%.

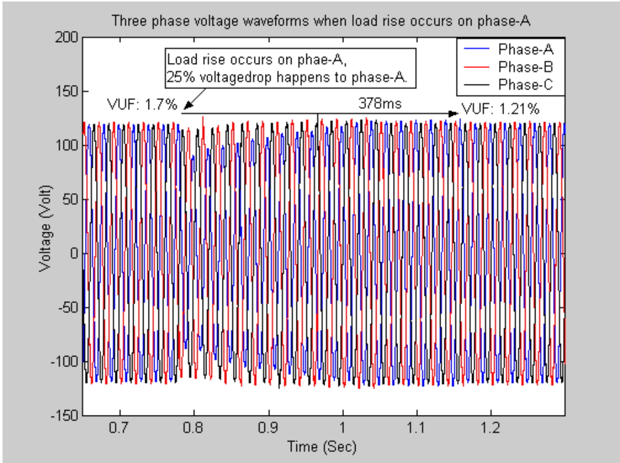

Fig. 9 Three-phase voltage when load rise occurs on phase-A

The response time is related to the severity of voltage unbalance and tap sizes of the tap changers, which determine the required tap change number. Moreover, by reducing the tap size, the VUF in the LV network could be reduced to a lower value, but the response time would increase.

CONCLUSION

This paper introduces an LV radial feeder balancing method using Scott transformers. This method is able to provide a balanced three-phase voltage at a downstream location on an LV feeder or at a three-phase load supply point. An experimental LV feeder test system is described and then used to evaluate the proposed balancing method. The test results demonstrate that the proposed method is capable of balancing the voltages on the LV network and maintaining the balance by continually compensating for voltage surges and sags caused by load variations.

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