FACTS BASED SUPPRESSING TECHNIQUES & DEVICE OF THREE-PHASE UNBALANCED OVERVOLTAGE FOR DISTRIBUTION NETWORKS

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ABSTRACT

The unbalanced phase-to-ground impedance of distribution network brings about three-phase unbalanced overvoltage in neutral non-effectively grounded system, which decreases the system reliability and deteriorates the security of power supply. Generally switched capacitors and controlled reactors encounter the inherent disadvantages such as low accuracy, slow response speed, complicated calculation of capacitor currents, etc. To solve this problem, a device based on the flexible grounding technique to suppress the three-phase unbalanced voltage is proposed. Flexible grounding technique is developed from the flexible alternative current transmission system (FACTS). By injecting zero sequence current to distribution network to compensate the unbalanced phase-to-ground current, zero sequence voltage would be controlled and the three-phase unbalanced overvoltage would be suppressed ultimately. This device consists of some power electronic devices and is able to eliminate the neutral point overvoltage by injecting a current into that point. The basic principle of the device is presented, accomplished by the dual-loop control method which contains the outer voltage loop and the inner current loop. A prototype in 380V system is established and the proposed principle and control method are validated by experimental results.

Keywords—non-effectively grounded distribution network; three-phase unbalanced overvoltage; flexible alternative current transmission systems (FACTS); flexible grounding; control method.

I. INTRODUCTION

With the development of smart grid, distribution network has played an exceedingly important role in supplying industrial and private electric power. The distribution network fault will directly affect the normal production of power consumers and the reliability of the power systems[1]-[2].

Neutral point non-effectively grounded method is widely applied in the distribution network. System of neutral grounding by resistance or by petersen-coil can generate zero sequence voltage[3]. Owing to the changing conditions in actual distribution network, neutral displacement voltage will be produced by unbalanced phase-to-ground impedances which results from unsatisfactory transposition, network operation with a single-phase load, or broken wire fault due to harsh environment. The neutral displacement voltage can result in cascading faults[4], so it is necessary to suppress the three-phase unbalanced overvoltage in distribution network.

Traditional suppressing method of three-phase unbalanced overvoltage is mainly to switch capacitor manually[5]. The three-phase voltage can recover its balance by putting capacitor bank into the unbalanced phase-to-ground capacitance phase. This method is advantageous in many aspects—it is simple，economical and convenient. However, due to the changeable condition of phase-to-ground capacitance in actual operation, this method is difficult to track and compensate the unbalanced overvoltage accurately and rapidly.

With the rapid development of power electronic technology, the three-phase unbalanced compensation measure, which is based on TSC (Thyristor Switch Capacitor)and TCR(Thyristor Switch Capacitor), has been widely used in actual operation[6].However, its disadvantage is that TCR and TSC could not be adjusted continuously. This two individual devices and their combination with capacitors in different forms are generally used nowadays to compensate the three-phase unbalanced parameters in distribution network[6]-[7]. Literature [8] presents a Compensation of unbalanced three-phase voltage method using SVC, which is the compose of TSC and TCR, the susceptance of SVC could be continuously adjusted by changing the conduction angle of TCR or switching groups of TSC ; Literature [9] presents a reactive power compensation technology of bidirectional thyristor controlled reactor and capacitor which combined with 12 pulse technology; Literature [10] proposes a new reactive power compensation method in distribution network by using transformer-isolated DSTATCOM. The above compensation devices can solve the unbalance problem result from the unbalanced load in distribution network, which improve the power factor and quality of distribution network to some extent. In actual operation, however, the three-phase unbalanced parameters in distribution network are mainly manifested as the unbalanced phase-to-ground current and the displacement voltage drift in neutral point, so none of the above compensation methods could suppress the three-phase unbalanced voltage fundamentally.

Flexible Alternative Current Transmission System (FACTS), which is a new concept in transmission technology, has recently been introduced and became an active research area[11]. It is defined by an IEEE Working Group as: "Alternating current transmission systems incorporating power electronic-based and other static Controllers to enhance controllability and increase power transfer capability[12]." This technology is based on power electronics, to enhance power system capability through the ability of high-speed electronic control of ac transmission line parameters. FACTS equipment provides the modern power system with very effective means to enhance its security, economy, reliability and high-quality operation[13]. At the heart of FACTS installations are the power electronic convertors which form the smartest part of the equipment. The key feature of FACTS is the availability of power electronic switching devices that can switch electricity at megawatt levels [14]. In order to make use of this advanced technology, a FACTS based new principle of flexible grounding device was presented to suppressing the three-phase unbalanced voltage [15].

In this paper, a novel FACTS based Suppressing device of three-phase unbalanced overvoltage is proposed. Flexible grounding technique is developed from the FACTS technique. By injecting zero sequence current to distribution network to compensate the unbalanced phase-to-ground current, zero sequence voltage was controlled and the three-phase unbalanced overvoltage was suppressed ultimately. This paper firstly analyzed the suppression principle of three-phase unbalanced overvoltage of distribution networks and presented the control method of flexible grounding device. Secondly, it introduced the whole software control process of the device. Lastly, it imitated the process of suppressing three-phase unbalanced overvoltage by the prototype. The results showed that the principle and control method were feasible.

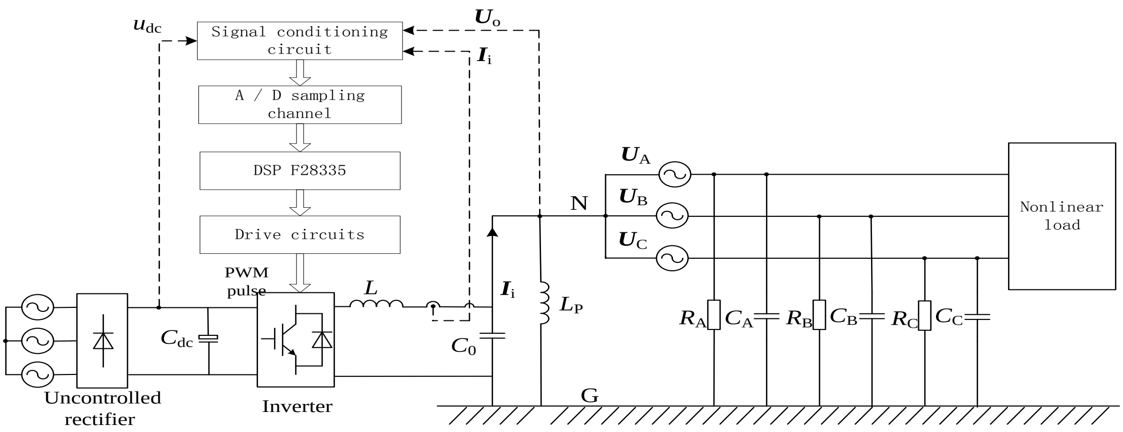

Fig.1 Suppressing device of three-phase unbalanced overvoltage system topology

II. SUPPRESSION MECHANISM OF THREE-PHASE UNBALANCED OVERVOLTAGE

Neutral displacement voltage equal to zero which is treated as the target of three-phase unbalanced overvoltage suppression. As is shown in Fig.1, the neutral point is grounded through the suppressing device. U_A, U_B, U_C are the three-phase supply voltages respectively. U_A represents neutral displacement voltage respectively. R_A, R_B, R_C denote the phase-to-ground leakage resistances of each phases, respectively. C_A, C_B, C_C denote the phase-to-ground capacitances of each phases, respectively. L_P represents the Petersen coil and I_i represents the injecting current. Closing the main contactor and the three-phase AC will be converted to single-phase DC by an uncontrolled rectifier. Then it will be converted to single-phase AC by an inverter and injected into the neutral point of distribution network. Voltage sensors collect DC voltage signal and voltage signal at neutral point while current sensor signal collects injecting current. After being processed by the signal conditioning circuit, the voltage and current signals will be sent to the A/D sampling channels and transmitted to the DSP control board. Pulse driving circuit generates PWM pulse signals by receiving and processing the samples which controls the on-off of IGBT and generates injecting current. To improve unbalanced overvoltage suppression effect and reduce the harmonic pollution to the grid, a LC filter circuit will be used first, and then the current will be injected into the distribution network.

At normal operating conditions of the grid, the asymmetry of three relatively leak resistance and capacitance generates the displacement voltage. To simplify the analysis, a controlled current source is used to substitute the suppressing device of three-phase unbalanced overvoltage. Thus, the circuit schematic of the system can be shown in Fig.2.

In Fig.2 I_{LA}, I_{LB}, I_{LC}, denote the three phase load current, respectively. The phase-to-ground capacitances of each phases are denoted by C_A, C_B, C_C while the impedances of then are represented by Z_A, Z_B, Z_C, respectively. Z_1, Z_2, Z_3 derive from the leakage resistance of each phases. The three phase supply voltages are assumed to be sinusoidal and only contain positive sequence components. The injected current from the suppressing device of three-phase unbalanced overvoltage is denoted by I_i. Seen by the Kirchhoff's voltage and current laws, the following expressions can be attained.

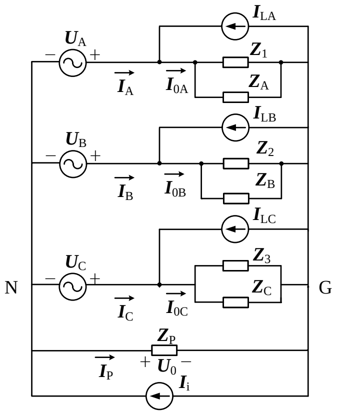

Fig.2 System circuit schematic

As the sums of the positive and negative sequence components of the three phase load current are both zero, the sums of the three phase load current can be expressed by the zero sequence components I_{L0} as follows. Typically, the zero sequence component I_{L0} is caused by the unbalance of the load as well as the zero sequence harmonics like the 3k order harmonic, et al.

$$\begin{cases} I_{0A} = I_A + I_{LA} \\ I_{0B} = I_B + I_{LB} \\ I_{0C} = I_C + I_{LC} \\ I_A + I_B + I_C + I_0 = I_i \end{cases} \tag{1}$$

$$\begin{cases} (Z_1 \parallel Z_A)\mathrm{I}_{0A} = U_A + Z_P I_P \\ (Z_2 \parallel Z_B)\mathrm{I}_{0B} = U_B + Z_P I_P \\ (Z_3 \parallel Z_C)\mathrm{I}_{0C} = U_C + Z_P I_P \\ U_0 = Z_P I_P \\ U_A + U_B + U_C = 0 \end{cases} \tag{2}$$

$$L_{LA} + L_{LB} + L_{LC} = 3I_{L0} \tag{3}$$

From the expressions (1) to (3), the injected current I_i can be expressed by equation (4) as follow.

$$I_i = \frac{U_0}{Z_P} + \frac{U_A + U_0}{Z_1 \parallel Z_A} + \frac{U_B + U_0}{Z_2 \parallel Z_A} + \frac{U_C + U_0}{Z_3 \parallel Z_A} - 3I_{L0} \tag{4}$$

$$I_i = \left(\frac{U_A}{Z_1 \parallel Z_A}\right) + \left(\frac{U_B}{Z_1 \parallel Z_B}\right) + \left(\frac{U_C}{Z_1 \parallel Z_C}\right) - 3I_{L0} \tag{5}$$

When the injected current of the suppressing device of three-phase unbalanced overvoltage is controlled to be the value in expression (5), the neutral displacement voltage U_0 would be restricted to zero, thus the three-phase unbalanced voltage would be extinguished.

III. CONTROL METHOD OF FLEXIBLE GROUNDING DEVICE

Because of poor anti disturbance performance for single closed loop control, the device adopts double loop control strategy, including the outer loop PI controller and inner deadbeat controller. Fig.3 is double closed loop control method functional block diagram.

A. outer loop PI controller

In order to simplify the control process, the voltage outer loop uses proportional integral controller. The control objective of the outer voltage loop is to restrain the neutral point displacement voltage to zero. The difference value between reference voltage u_N^* and measured value U_N of the neutral point will be used as the input of PI controller. After limiting the amplitude of the output, here comes the amplitude of the directive current I_S^*:

$$I_s^* = K_P\left(1 + \frac{K_I}{s}\right)(u_N^* - u_N) \tag{6}$$

K_P is the proportionality coefficient; K_I is the integral coefficient;

$$G_{outer} = \frac{G_{PI} G_{inner} Z_{\mathrm{II}}}{1 + G_{PI} G_{inner} Z_{\mathrm{II}}} \tag{7}$$

$$G_{PI} = K_P\left(1 + \frac{K_{\mathrm{I}}}{s}\right) \tag{8}$$

$$Z_{\mathrm{II}} = Z_P \parallel (Z_1 \parallel Z_A) \parallel (Z_2 \parallel Z_B) \parallel (Z_3 \parallel Z_C) \tag{9}$$

G_{inner} is the Inner loop transfer function.

B. Inner loop deadbeat controller

The current inner loop is to realize the real-time tracking of the injection current and is the key part of the control system. The deadbeat control is used in inner voltage loop to realize the high precision control of zero-sequence current and injection current. At the end of each sampling period, the deadbeat control is that the neutral point current can track the reference current. Ignoring the filter's impedance, the equation of deadbeat control can be expressed as

$$U_{inv}(\mathrm{k}) = \mathrm{U}_{s\_av}(\mathrm{k}) + \frac{L_s}{T_s}[\mathrm{i}_s^*(\mathrm{k}+1) - \mathrm{i}_s(\mathrm{k})] = \mathrm{D}(\mathrm{k})\,\mathrm{U}_{dc}(\mathrm{k})$$

where, T_s is power device switching cycles; L_s is the filter inductance; $i_s(k)$ is sampling current at k time; $U_{inv}(k)$ is the average output voltage value of inverter at k time; $U_{s\_av}(k)$ is the average value of neutral point displacement voltage at k time; $D(k)$ is The duty factor of switching tube; $U_{dc}(k)$ is the average voltage value of sampling period.

According to the equation, the output voltage of inverter at k+1 time —which is $U_{ink}(\mathrm{k})$—can be calculated by $i_s(\mathrm{k})$, $u_{s\_av}(\mathrm{k})$ and $i_s^*(\mathrm{k}+1)$. In this way can the deadbeat control be achieved.

According to Fig.3, the transfer function of inner loop voltage is:

$$G_{inner} = \frac{L_s k_{inv} Z_I}{T_s^2 s + T_s - T_s k_{inv} Z_I Z_{II} + L_s k_{inv} Z_I} \tag{10}$$

where, $Z_{\mathrm{I}} = \frac{1}{sL_s}$, k_{inv} is the equivalent gain of inverter.

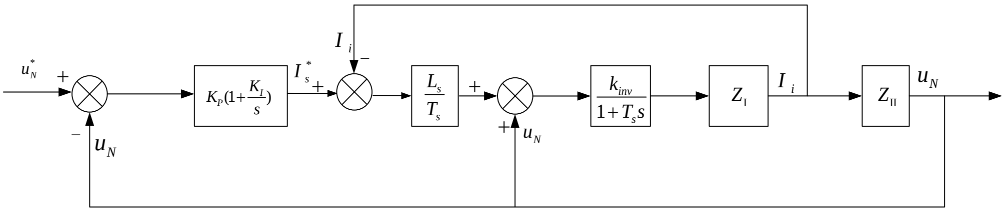

Fig.3 Double closed loop control method functional block diagram

IV. EXPERIMENTAL RESULTS ANALYSIS

According to the analysis of suppressing principle and the control method of the double-loop, we have designed a FACTS based overvoltage suppressing prototype and have set up a distribution network test model to carry out the three-phase unbalanced suppression experiment. The test achieved the expected targets and the results were following.

Distribution network simulation is shown in Fig. 1: the line leak resistance of A-phase and B-phase are both 1600Ω and the line-to-ground capacitance are both 100uF, leakage resistance of C-phase is 1600Ω and phase-to-ground capacitance is 200uF. The Three-phase to ground voltage is 380V. The experimental results can be gained through the real time dynamic observation of the three-phase voltage to earth, which are U_{AG}, U_{BG}, U_{CG}, voltage at neutral point, which is U_{NG} and the injecting current I_i by fluke power quality analyzer. Waveforms of phase-to-ground and neutral voltages before current injection are shown in Fig. 7. The phase-to-ground voltages of A phase, B phase, C phase, are respectively 251.6V, 240.6V, 220.5V, voltage at neutral point is 54.6V. The system is running under three-phase unbalanced state. Putting the three-phase unbalanced overvoltage suppression device into the system and we can see that the waveform of the injecting current is close to a sine wave. As is shown in Fig. 8, the Injecting current waveform has low harmonic content and its value is 9.8A. Also, we can know from Fig 9 that The voltage waveforms of A-phase, B phase, C phase tend to be three-phase balanced and the three-phase unbalanced voltage has been suppressed, which can be seen by the reduction of The neutral point voltage — it has dropped from 54.5V to 4.6V. So the principle and control method has proved to be correct.

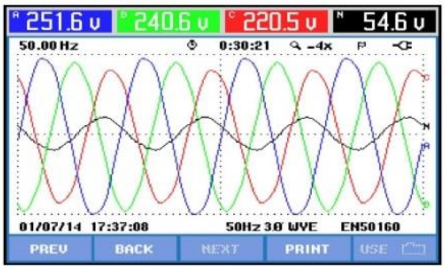

Fig.6 Waveform of phase-to-ground and neutral voltages before current injection

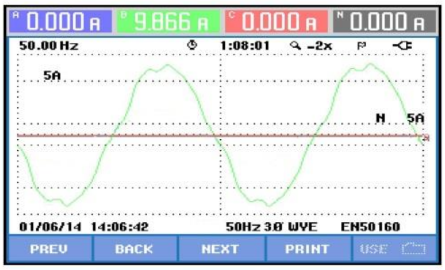

Fig.7 Injecting current waveform

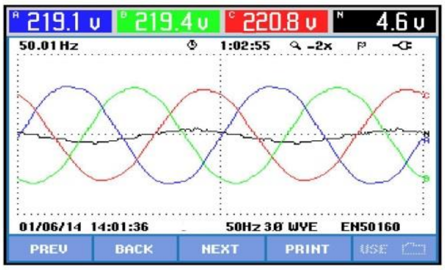

Fig.8 Waveform of phase-to-ground and neutral voltages after current injection

V. CONCLUSION

A new principle presented by this paper and showed that it can suppress the three-phase unbalanced overvoltage in distribution network: injecting zero sequence current in neutral point to control the zero sequence voltage and the method could suppress the three-phase unbalanced overvoltage dynamically. At the same time, a double closed-loop controlling method of flexible grounding device was presented. Through the method which uses neutral displacement voltage and current as the feedback, the change of phase-to-ground parameters could be tracked quickly and accurately. It also has the ability to change the amplitude and the phase of the injection current to compensate the zero sequence voltage dynamically. With this method, three-phase unbalanced overvoltage could be restrained finally. The test data in the simulation of distribution network demonstrated the correctness of the principles, and realized the suppression of three-phase unbalanced overvoltage and neutral displacement voltage.

REFERANCES

[1] IEEE recommended practice for grounding of industrial and commercial power systems, IEEE Std 142-2007[S]. 2007, p 17-80.

[2] Griffel D.; Leitloff, V., 1997, “A new deal for safety and quality on MV networks”. *IEEE Transactions on Power Delivery*, v 12, n 4, p 1428-1433.

[3] Yao Huannian; Cao Yuemei, 2009, *Power system resonance grounding Theory*. Beijing, China, p 34-36 .

[4] Bina, M. Tavakoli; Kashefi, A. 2011,"Three-phase unbalance of distribution systems: Complementary analysis and experimental case study" *International Journal of Electrical Power and Energy Systerms*, v 33, n 4, p 817-826.

[5] Farhad Shahnia; Peter J. Wolfs; Arindam Ghosh, 2014,"Voltage Unbalance Reduction in Low Voltage Feeders by Dynamic Switching of Residential Customers Among Three Phases" *IEEE Transactions on Smart Grid*, v 5, n 3, p 1318-1327.

[6] Reed, G. ; Paserba, J. ; Croasdaile, T.,2011, "The VELCO STATCOM based transmission system project" *Proceedings of the IEEE Power Engineering Society Transmissionand Distribution Conference*, v 3, p 1109-1114.

[7] Leon, Andres E.; Mauricio, Juan Manuel, 2009,"Software sensor-based STATCOM control under unbalanced conditions" *IEEE Transactions on Power Delivery*, v 24, n 3, p 1623-1632.

[8] Tong Xiangqian; Wang Haiyan; Yin Jun ,2011,”Calculation method of three-phase unbalance factor based on load power”. *Proceedings of the CSU-EPSA*, v 23,n 2, p 1-7.

[9] Yuan Xufeng, Gao Lu, 2010, “Three-phase unbalanced control strategy for VSC-HVDC”. *Electric Power Automation Equipment*, v 30 n 9, p 1-5.

[10] Singh, B.; Saha, R.;Chandra, A., 2009, "Static synchronous cpmpensators (STATCOM): A review" *IET Power Electronics*, v 2, n 4, p 297-324.

[11] Senjyu, T.; Molinas, M.,1996, “Multi-Machine Power System Stabilization with FACTS Equipment Applying Fuzzy Control ” , *Proceedings of the 35th IEEE Conference*,v 2, p 2202-2207.

[12] Narain G., Hingorani, 2007, “FACTS Technology – State of the Art, Current Challenges and the Future Prospects”. *Power Engineering Society General* , p 1-4.

[13] Adibi, M.M.; Martins, N., 2010, “The impacts of FACTS and other new technologies on power system restoration dynamics”. *Power and Energy Society*, p 1-6.

[14] Edris, A, 2000 “FACTS technology development: an update”. *Power Engineering Review, IEEE*,v 20, n 3, p4-9.

[15] Zeng Xiangjun, Wang Yuanyuann, 2012, “Novel principle of faults arc extinguishing & feeder protectionbased on flexible grounding control for distributionnetworks”. *Proceedings of the CSEE*, v 32, n 16, p 137-143.