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To cite this article: P S Pinchukov 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **272** 022070

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Modelling of Dynamic Compensation for Isolated Neutral Power Network

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Abstract. The paper deal with causes and consequences of the negative influence of harmonic components of currents and voltages in medium voltage distribution networks. The dynamic compensation benefits for filtering harmonic components of currents and voltages and eliminating current and voltage distortion from the power system are considered. In the paper the model of isolated neutral power network with the dynamic compensation device is created by simulation in the Matlab Simulink software. In the model a three-phase network was simulated by blocks from the SimPowerSystem database and the non-sinusoidal load was simulated by a three-phase bridge diode rectifier. The dynamic compensation filtering device is simulated by an inverter on IGBT-transistors and consisted of shunt reverse diodes, smoothing filters and capacitive storage. The simulation results show the reduction of the voltage distortion limits to the normalized values, thus we can eliminate the non-sinusoidal form of the voltage curve and make it sinusoidal by dynamic compensation in the distribution network. The dynamic compensation device operates correctly in the created model and is suitable for high-nonlinear, inductive, fast-changing and harmonic-generating loads, as it effectively fights against the violation of the quality of electrical energy.

1. Introduction

Medium voltage power distribution networks are used for distribution in urban and rural areas [1-4]. According to the world classification and the standard [2], most countries in the world use medium voltage networks for nominal voltage from 1 to 69 kV, and as Russia - starting from 1 and reaching up to 35 kV. Despite the possibility of using various types of neutral grounding for these networks, isolated neutral grounding is still used in a number of countries: Japan, Finland, Italy and Russia [4].

Isolated neutral type is the most simple and the first appeared in the electrical networks grounding of neutral in the power networks. For the first time it was introduced at Frankfurt exhibition by the system's developer, Russian engineer M.O. Dolivo-Dobrovolsky for the three-phase power transmission line Laufen - Frankfurt of 15 kV in 1891 and it still widely used in medium voltage power distribution networks in the world. Also, these electric networks are commonly used to providing train movement system (for example, distribution power network for supply signaling, centralizing and locking devices) in Russia and other countries like China, India, etc. [1-4].

Furthermore, due to the common power centers with the traction load, higher levels of higher harmonic components of currents and voltages are observed in the electrical networks [5]. This fact can be explained by the non-linear loads – such as thyristor drives, converters and arc furnaces - specifically connected to these networks, excessive harmonic current are generated, and this causes both current and voltage distortion [5 - 7]. When a non-linear load is connected to the power system,



like modern trains with its power electronic converters, other frequency components are generated, usually higher than the fundamental frequency. These higher (or older) frequency components of the voltage or current signals are designated harmonics [7].

In most occasions, the problem of harmonic components of currents and voltages in medium voltage power distribution networks is the overvoltage [5, 7-9]. The overvoltages are result of harmonic distortion close to resonant frequencies are characterized by a significant increase of peak value (crest) and a moderate increase in the root mean square (RMS) value [7-11]. The overvoltage cause stress to the apparatus internal insulation and reduces their lifecycle. Equipment faults due to internal insulation breakdown and consequent system outages are frequent when subjected to severe overvoltage over a period of time. High amplitude peak voltages can result in rapid apparatus faults whilst lower amplitude peak voltages have long-term effects [5, 7, 11].

Because of the paramount necessary of electromagnetic compatibility at power supply level between fixed installations and rolling stock, dealing with power quality, system availability and reliability, it is customary to filter out the older harmonic components of currents and voltages by means of special devices named harmonic filters [5, 12-14]. In another words, harmonic filtering is the best way to eliminate current and voltage distortion from the power system.

In order to solve more serious harmonic problems of the power distribution networks, the passive power filter (PPF), the active power filter (APF) and the hybrid active power filter (HAPF) are often used at the point of common coupling (PCC) conventionally [3, 5, 12-14]. It is important to note, that compensation systems without the power electronics unit, consist of such elements as thyristor, diode and transistor, are designed for the pure power factor optimization and also can effectively reduce the harmonics level, but are not able to keep up with fast load changes in a shot time interval and do not provide a satisfactory solution [12-16].

Dynamic (delay-free) reactive power compensation systems (i.e. with thyristor-switched capacitors) can prevent or reduce network perturbations such as brief drops in voltage and flicker in cases of non-linear loads and of rapid load changes. In international technical language sometimes the following terms are commonly used: "fast switching dynamic power factor correction", "dynamic compensation" or "dynamic power factor correction system" and sometimes referred to as "real-time power factor correction", is used for electrical stabilization in cases (e.g. at large manufacturing sites) [15, 16]. The dynamic reactive power compensation systems uses semiconductor switches, typically thyristors, to quickly connect and disconnect capacitors or inductors to fast and effective operation.

Because of that, the dynamic reactive power compensation systems seem to be a feasible solution for eliminating harmonic currents and voltages in many difficult cases such as railways power network system operation, distribution power network for supply signaling, centralizing and locking railway devices, etc.

2. Materials and Methods

In this study, we used experimental research methods, based on nature measurement of control parameters and subsequent modelling and analysis. The measurements were carried out for power distribution line of 10 kV, 50 Hz, located at Far Eastern region of Russia. In our research, we aim to assess the possibilities of using dynamic reactive power compensation system for filtering harmonics in medium voltage distribution network 10 kV, which have the common feeding centers with the traction loads of AC power network. Also the model of medium voltage power distribution network was created by simulation in the MATLAB Simulink software.

3. System configuration and modelling strategy

3.1. Topology of the isolated neutral distribution network with dynamic compensation system

The scheme of the considered isolated neutral power distribution network with the dynamic compensation device is shown at figure 1.

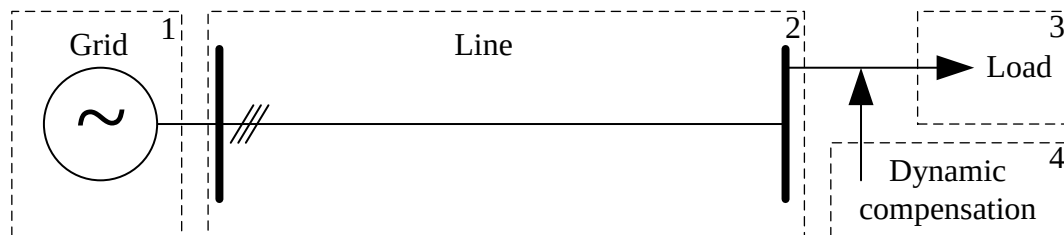


Figure 1. The considered power distribution network configuration.

The considered system is consist on four main blocks, numbered at figure 1: a block 1 – a grid of AC, 50 Hz; a block 2 - a three-phase high-voltage distribution isolated neutral line; a block 3– the three single-phase loads (non-linear, non-symmetrical and non-sinusoidal), which are sequentially included in each phase of the line and a block 4 - the three-phase dynamic filtering device (or, in other words, compensation device). For the simulation of three-phase network in the MATLAB Simulink software was used the AC Voltage Source and Series RL Branch blocks from the SimPowerSystem database. The topology of the isolated neutral distribution network with dynamic compensation system is shown at figure 2. As we can see at figure 2, the circuit is supplemented with blocks for current and voltage measurements.

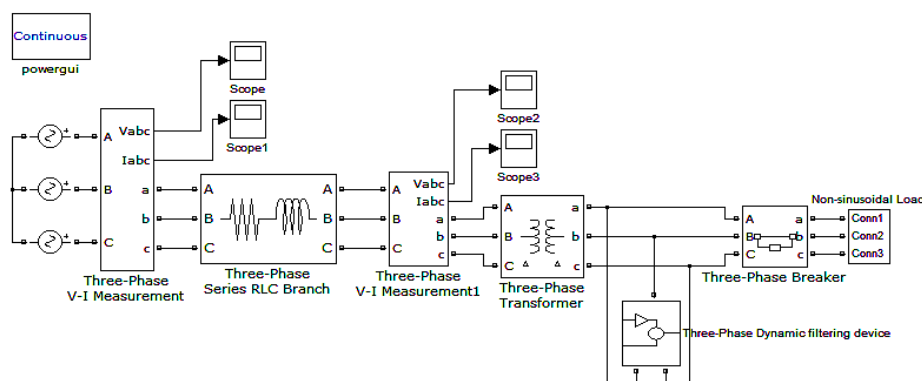


Figure 2. Topology of the isolated neutral distribution network with dynamic compensation system.

3.2. Setting the main blocks parameters

Using the above-mentioned blocks, we set the parameters of the three-phase symmetrical voltage power grid a frequency of 50 Hz by setting for each AC Voltage Source block three-phase offset by 120 degrees.

The following parameters was set: the AC line length is 50 km; the aluminum and steel wire of 50 square mm, it's active resistance is 29.75 Ohm and inductance - 16.7 mH. For the simulation of the three-phase line in the MATLAB Simulink software was used the three-phase series RL branch block.

In the considerate electrical system there are sources of non-sinusoidal currents and voltages - these are electrical receivers with a nonlinear voltage-current characteristic. Thus, for modeling the non-sinusoidal load we use the Universal Bridge block from the SimPowerSystem database as recommended in [17]. According to the recommendations of [18], we set the following parameters for modern high-power diodes: the diode on-state resistance is 0.01 Ohms; the diode on-state inductance is 0 Hz, the minimum voltage the anode-cathode opening of the diode is 1 V.

Thus, we have chosen the parameters of the non-sinusoidal load so that it creates in the system the spectra of harmonics of currents and voltages the same as in real operating conditions. Previously, we determined and described in [5, 6] the spectra of currents and voltages harmonics at the system control points by the electricity quality indices measured during experiment. As a result of the experiment, As

a result of the experiment it was established that in the control points the following harmonics of voltages must be filtered: for U_A and U_B - 4, 5 and 21 harmonics, for U_C - 2, 4 and 5 harmonics [5, 6].

Modeling of dynamic filtration device was produced according to the recommendations given in the textbooks and articles [17-22]. The dynamic compensation device is connected to the network in parallel with the load and set behind the transformer for the excluding a special (separate) transformer for the device itself. The device contains six IGWT-transistors with shunt reverse diodes. These diodes serve to exclude the possibility of the appearance of reverse voltage on the transistors.

To ensure electromagnetic compatibility and smoothing the harmonics generated by the device itself, it is connected to the network through inductors (chokes). On the DC side there is a capacitive accumulator, the current of which assumes pulsating values: positive - during operation of reverse diodes, and negative - during operation of transistors.

4. Dynamic compensation device control system

The main unit of the dynamic compensation device is a control system operating in two stages: the first is the allocation of an information signal, the second is the switching of power switches (transistors). The information signal determination is based on the d-q transformation method using the Clarke and Park transforms [18, 22], or, in other words, the instantaneous three-phase power transformations into the power of a two-phase system that rotate in a space with a phase shift.

The relationship between AC and DC currents and voltages is determined by the equations:

$$u_{DC} = G_{AC} \times \begin{vmatrix} m_a \\ m_b \\ m_c \end{vmatrix} \times \begin{vmatrix} u_{af} \\ u_{bf} \\ u_{cf} \end{vmatrix} \quad (1)$$

$$\begin{vmatrix} i_{af} \\ i_{bf} \\ i_{cf} \end{vmatrix} u_{DC} = G_{AC} \times \begin{vmatrix} m_a \\ m_b \\ m_c \end{vmatrix} \times i_{DC} \quad (2)$$

To display the formulas to avoid confusion, we use the index f to denote the parameters related to the dynamic compensation device, in this case the f index means the filtering device (the meaning is the same). The components u_{DC} in equation (1) and i_{DC} in equation (2) is the DC voltage and current respectively. The component G_{AC} in equation (1) and (2) is the inverter transfer coefficient and the components m_a , m_b , m_c are the modulation vectors. The components u_{af} , u_{bf} , u_{cf} and i_{af} , i_{bf} , i_{cf} in equations (1) and (2) are the dynamic filtering device voltage and current respectively.

Neglecting the inductance of the line, we obtain the differential equations (3) – (6) of the three-phase dynamic filtering device:

$$L_f \frac{di_{af}}{dt} = u_{aLine} - u_{af} \quad (3)$$

$$L_f \frac{di_{bf}}{dt} = u_{bLine} - u_{bf} \quad (4)$$

$$L_f \frac{di_{cf}}{dt} = u_{cLine} - u_{cf} \quad (5)$$

$$C_f \frac{du_{DC}}{dt} = f_a i_{af} + f_b i_{bf} + f_c i_{cf} \quad (6)$$

The component L_f in equations (3), (4) and (5) is the inductance of smoothing coils of the dynamic compensation device. The component C_f in equation (6) is the storage capacitor capacitance.

of the dynamic compensation device. The components f_a , f_b , f_c in equation (6) have a switching functions that take values equal to 0, $\pm 1/3$ and $\pm 2/3$, respectively [22].

Next, we turn to the d-q coordinates system and obtain the following equations (7)-(9) for dynamic compensation device:

$$L_f \frac{d\mathbf{i}_{df}}{dt} = u_{dGrid} + \omega_{Grid} L_f \mathbf{i}_{df} - u_{df}, \quad L_f \frac{d\mathbf{i}_{qf}}{dt} = u_{qGrid} + \omega_{Grid} L_f \mathbf{i}_{qf} - u_{qf} \quad (7)$$

$$C_f \frac{du_{DC}}{dt} = 2/3(f_d i_{df} - f_q i_{qf}) \quad (8)$$

$$u_{df} = f_d u_{dGrid}, \quad u_{qf} = f_q u_{qGrid} \quad (9)$$

The component ω_{Grid} in equation (7) is the grid mains frequency. Components d and q in equations (7)-(9) are the indices for the designation of d-q axes. Thus, the equations (7) – (9) represent the basis for the control system without using a fast Fourier transform, which makes it possible to generate signal into the network with the shortest time delay.

For switching by transistors we will use the method of "tracking" or hysteresis modulation, also called – the “delta modulation”. The principle of this method is to monitor the actual load current and compare it with the ideal current given by the law of modulation [22]. The switch device consists of a proportional-integral link (named PI-controller), which receives the difference between the ideal and actual current, and then the signal is transmitted to the relay-pulse comparator, where the regulation of the current and voltage deviations is set by the width of the hysteresis loop.

We use the "Monitoring" block by MATLAB for the control system blocks modeling. Firstly, the ideal sinusoid is generated in that block. The sinusoid coincides in phase with the root-mean-square value of the load voltage. If an error was detected by virtual meters between the ideal and genuine sinusoid, the power switches were switched according to a predetermined algorithm, and the dynamic filtering device generates a signal to the network with a small delay in time, thereby bringing the form of the voltage on the load closer to an ideal sinusoid. A resulting simulated three-phase dynamic filtering device model is shown at figure 3.

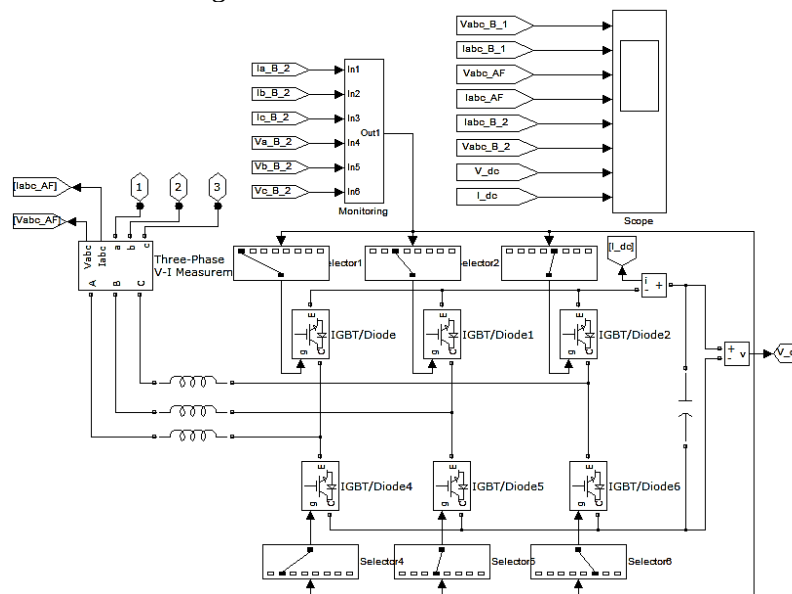


Figure 3. Three-phase dynamic filtering compensation device model.

5. Results

The simulation results in the form of voltage curves and total harmonic distortion of voltage (THD_U) for cases when the compensation device is switched-off are shown at figure 4 and the compensation device is switched-on - at figure 5.

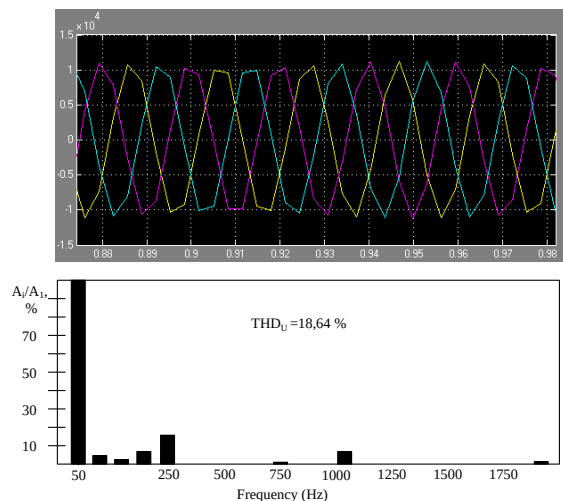


Figure 4. Voltage curves and total harmonic distortion of voltage. The dynamic compensation device is switch-off

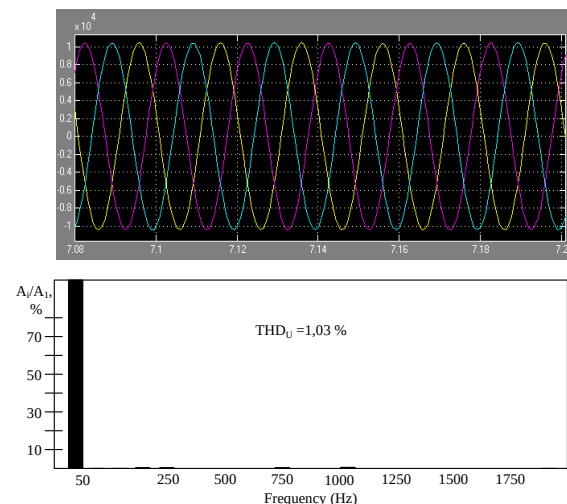


Figure 5. Voltage curves and total harmonic distortion of voltage. The dynamic compensation device is switch-on

As we can see, the harmonic filtering due the dynamic compensation device decreases the total harmonic distortion in considered system from 18.64% to 1.03%, i.e. in 18 times. This proves the effectiveness of using this type of device for normalizing sinusoidal form of the voltage curve in isolated neutral power network.

6. Discussion

The simulation results show the reduction of the voltage distortion limits to the normalized values, thus we can eliminate the non-sinusoidal form of the voltage curve and make it sinusoidal by dynamic compensation in the distribution network. The proposed control signal allocation system allows minimizing key elements, reducing the cost and dimensions of the dynamic filtering device. In our opinion, it is expedient to locate this device at the points of common coupling as far as it possible to a non-sinusoidal load.

7. Conclusion

Summarizing the results we can conclude the following points:

1. The dynamic compensation device operates correctly in the created isolated neutral power network model and is suitable for high-nonlinear, inductive, fast-changing and harmonic-generating loads.
2. The dynamic compensation device effectively fights against the violation of the quality of electrical energy and can be recommending for distribution isolated neutral power network which supply signaling, centralizing and locking railway devices.

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