A DEVELOPMENT OF SHUNT REACTOR CONTROLLED ENERGIZING THEORY

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Introduction

The uncontrolled energizing of shunt reactors is accompanied by appearance of a significant DC-component in current, leading to saturation of power and instrument transformers in adjacent network [1, 2]. DC-component causes high inrush current that have an electrodynamic impact on power network equipment [3]. In order to prevent these negative consequences, controlled switching devices providing reactor optimal energizing instant are used.

The optimal energizing phase of single-phase shunt reactor corresponds to peak of supply voltage. Energizing of three-phase reactor differs from energizing of single-phase reactor, mainly due to mutual electrical and/or magnetic coupling between phase windings. In other words, the choice of optimal energizing phases of three-phase shunt reactor depends on windings connection scheme and magnetic core design.

In this paper a universal method for determining the optimal energizing instant for all types of three-phase shunt reactors is proposed. The optimal energizing is considered as providing conditions to prevent DC-component in reactor current.

Successful operation of controlled switching devices is achieved due to monitoring a switching process and if necessary appropriate correction of estimation of circuit breaker operation time. In this regard, it is important to precisely evaluate circuit commutation moment.

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In order to ensure high accuracy of monitoring a switching process, modern controlled switching devices measure feedback signals with high sampling frequency (about 10 kHz) [3]. It complicates practical implementation of controlled switching function in intelligent electronic devices which usually have a relatively low sampling rate. Therefore, there is a need for solving the task of determining a real switching moment without increasing sampling frequency of ADC.

In this paper a new method for determining a real switching moment is proposed. The method based on adaptive structural analysis of transient current.

A single-phase shunt reactor energizing processes

Consider an energizing of single-phase reactor (Figure 1) form sinusoidal voltage source

$$u_s(t) = U\sin(\omega t + \psi),$$

supposing that switching moment is $t = 0$.

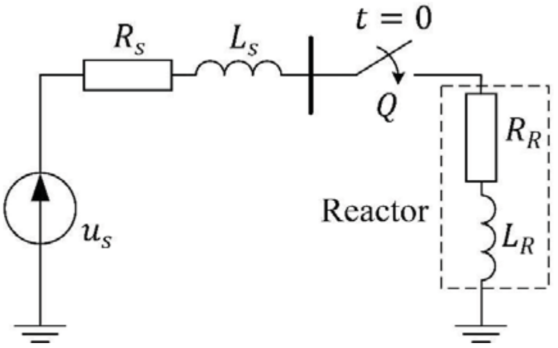


Figure 1 - Equivalent circuit during shunt reactor energizing

Current in the reactor after switching contains a steady-state

$$i_{\mathrm{st}}(t) = \frac{U}{Z_\Sigma}\sin(\omega t + \psi - \varphi) = I_{\mathrm{st}}\sin(\omega t + \psi - \varphi) \tag{1}$$

and free

$$i_{\mathrm{fr}}(t) = I_{\mathrm{fr}}e^{-t/\tau} \tag{2}$$

components where

$$\underline{Z_\Sigma} = (R_S + R_R) + j\omega(L_S + L_R) = Z_\Sigma e^{j\varphi} -$$

impedance of entire circuit.

As reactor impedance is much more than system impedance $Z_R \gg Z_S$ the current is determined mainly by reactor impedance. Existing reactors have a low active losses (according to [4], their resistance $R_R \leq 0{,}0036X_R$), and it is acceptable to assume that

$$Z_\Sigma \approx X_R = \omega L_R \tag{3}$$

and

$$\varphi = \arg\{\underline{Z_\Sigma}\} \approx \pi/2. \tag{4}$$

The reactor current before commutation is equal to zero. Therefore, initial current after commutation is described by equation

$$i(0) = i_{\text{fr}}(0) + i_{\text{st}}(0) = 0.$$

Initial values of free and steady-state current components will have equal magnitude and opposite sign:

$$i_{\text{fr}}(0) = -i_{\text{st}}(0). \tag{5}$$

Considering together equations (1), (2) and (5) with regard to (3) and (4), it is possible to define a ratio of initial values of free I_{fr} and steady-state I_{st} components of reactor current:

$$\frac{I_{\text{fr}}}{I_{\text{st}}} = -\cos\psi. \tag{6}$$

Optimal switching moment corresponds to supply voltage phase $\psi = \pi/2$ or $\psi = 3\pi/2$. Switching at these moments provides complete suppression of DC-component in reactor current. Usually, as a set point is taken angle

$$\psi_{\text{set}} = \pi/2.$$

Energizing of each phase winding of three-phase shunt reactors leads to potential change of other windings due to mutual electrical and/or magnetic coupling between phase windings. As a result, optimal switching time of three-phase reactor differs from optimal switching time of single-phase reactor. Optimal switching conditions of three-phase shunt reactor depends on its windings connection scheme and design of magnetic core.

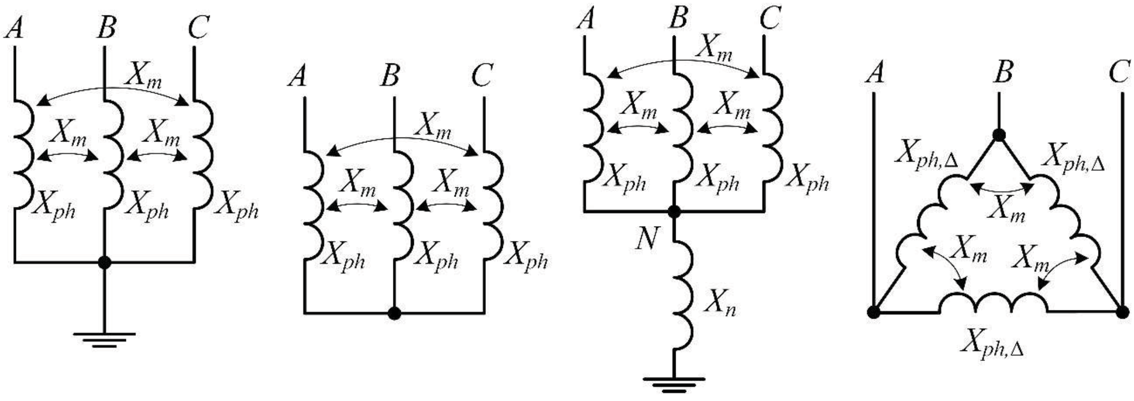
Three-phase shunt reactors design and their features

Four types of windings connection scheme of three-phase shunt reactor with a single magnetic core are the most common: a star with grounded neutral, a star with isolated neutral, a star with neutral grounding reactor and a delta connection. Obviously, schemes a) and b) on Figure 2 can be considered as special cases of scheme c) if we assume that the neutral reactor reactance $X_n = 0$ and $X_n = \infty$ respectively.

A delta connected circuit can be converted by known formulas into an equivalent star connected circuit with isolated neutral. Reactance of equivalent star circuit will be

$$X_{ph} = \frac{X_{ph,\Delta} - X_m}{3}.$$

Hence delta-connected three-phase shunt reactor commutation processes can also be analyzed in equivalent star connected circuit with neutral grounding reactor [5].



a) b) c) d)

Figure 2 - Windings connection scheme of three-phase shunt reactor:
a) star with grounded neutral; b) star with an isolated neutral; c) star with neutral grounding reactor; d) delta

Define a ratio of neutral reactance to phase reactance of reactor as

$$k_n = \frac{X_n}{X_{ph}},$$

and a ratio of mutual induction reactance to phase reactance as

$$k_m = \frac{-X_m}{X_{ph}}.$$

Mutual induction reactance X_m always has a negative sign. This is due to the fact that magnetic fluxes of self-induction and mutual induction are directed oppositely.

A mutual influence between phases for reactors with four- and five-limb magnetic core is absent, therefore $k_m = 0$. Energizing of one phase of shunt reactors with a three-limb magnetic core leads to appearance of a voltage in other two phases due to magnetic coupling between phases. Coefficient k_m of such type reactor is in range from –0.09 to –0.11 [6].

Thus, all types of three-phase reactors may be represented as a star connected reactor with neutral grounding reactor, and the optimal energizing conditions for all types shunt reactors can be determined by analysis of three-phase star connected reactor with neutral grounding reactor energizing processes (Figure 2, c).

Energizing of three-phase star connected shunt reactor with neutral grounding reactor

Transient process caused by energizing of each phase of shunt reactor can be studied using superposition theorem considering energizing as a sum of process in schemes of initial (Figure 3) and additional (Figure 4) modes. Free components of transient process arise in additional mode scheme; therefore, the optimal energizing moment can be determined from consideration of this scheme only.

Schemes of all additional modes are represented as EMF source $\underline{U}_{Q,\sigma}$, $\sigma = \overline{A, B, C}$ connected to inductive element. Value of $\underline{U}_{Q,\sigma}$ is equal to voltage across circuit breaker before commutation (in full scheme). Therefore, the optimal switching moment corresponds to phase of EMF source in additional mode scheme [7]

$$\arg(\underline{U}_{Q,\sigma}) = 90°. \tag{7}$$

Usually a phase voltage is used as a reference signal in controlled switching devices. Let us assume for definiteness that synchronization is carried out using phase voltage $\underline{U}_A$ as reference and produced in sequence A–B–C. Then complex amplitude of voltage on circuit breaker contacts of each phase can be expressed through complex amplitude $\underline{U}_A$:

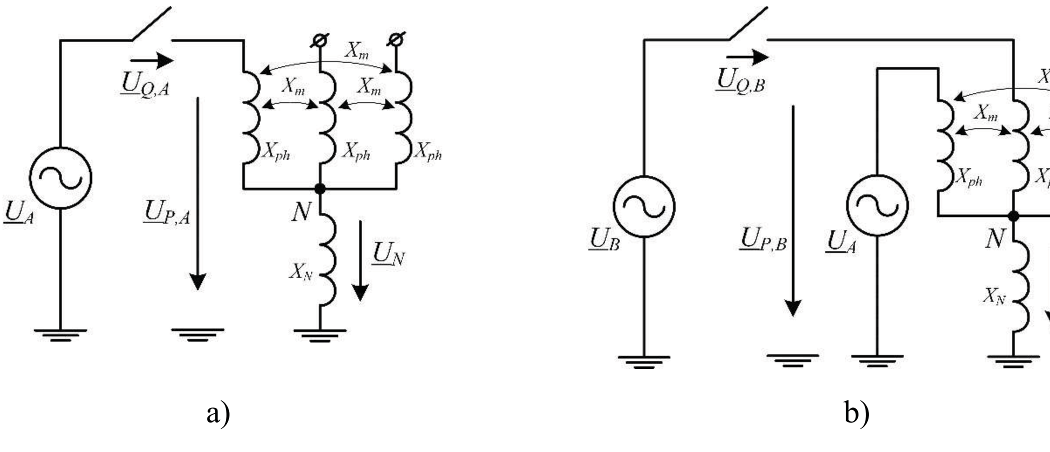
$$\underline{U}_{Q,\sigma} = \underline{U}_A \underline{\xi}_\sigma, \tag{8}$$

where complex coefficient $\underline{\xi}_\sigma$ calculated on the basis of shunt reactor design. Taking into account optimality condition (7), the target optimal phase of energizing will be

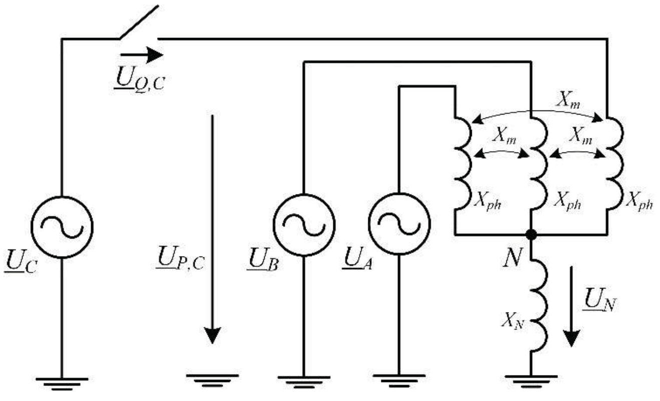
$$\psi_{\mathrm{opt},\sigma} = \arg(\underline{U}_A) = 90° - \arg\left(\underline{\xi}_\sigma\right). \tag{9}$$

Before energizing the first phase (Figure 3, a) voltage at breaker contacts is equal to reference phase voltage

$$\underline{U}_{Q,A} = \underline{U}_A - \underline{U}_{P,A} = \underline{U}_A.$$

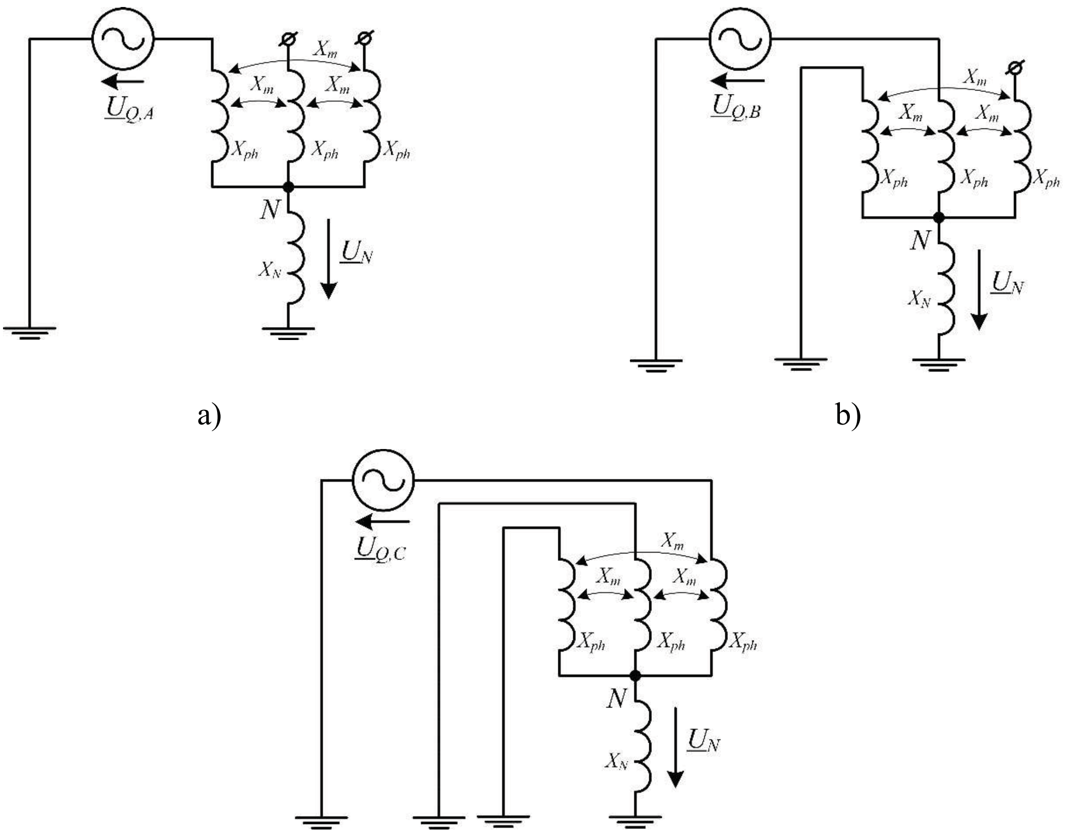


a) b)



c)

Figure 3 - Equivalent circuits of initial modes of shunt reactor phases energizing: A (reference phase) (a), B (b) and C (c)



a) b)

c)

Figure 4 - Equivalent circuits of additional modes of shunt reactor phases energizing: A (reference phase) (a), B (b) and C (c)

Consequently, $\underline{\xi}_A = 1$ and optimal energizing moment of first phase will be corresponded to reference voltage phase

$$\psi_{\mathrm{opt},A} = 90^\circ.$$

As can be seen from Figure 3b, energizing of first phase will cause arising of neutral reactor potential up to value

$$\underline{U}_{P,B} = \underline{U}_A \frac{X_n + X_m}{X_n + X_{\mathrm{ph}}} = \underline{U}_A \frac{k_n + k_m}{k_n + 1}.$$

Then the voltage at breaker contacts of the second phase

$$\underline{U}_{Q,B} = \underline{U}_B - \underline{U}_{P,B},$$

will be associated with the reference voltage according to (8) using the coefficient

$$\underline{\xi}_B = e^{j\psi_B} - \frac{k_n + k_m}{k_n + 1}.$$

In third phase (Figure 3, c) the complex coefficient is equal to

$$\underline{\xi}_C = e^{j\psi_C}\left(1 + \frac{X_n + X_m}{X_{\mathrm{ph}} + X_m + 2X_n}\right).$$

Optimal energizing conditions for three-phase shunt reactors

Let us assume that power source is represented by a three-phase positive sequence EMF system. For this case optimal energizing phases of various design three-phase shunt reactors are given in Table 1.

Since a first phase energizing of reactors with isolated neutral does not cause any current flow, first phase can be switched at any moment. Then the next two phases can be energized half a period earlier when breaker contacts voltage phase is –90°. According to (9), the optimal energizing moment of second phase will corresponds to angle $\psi_{\mathrm{opt},B} = -90^\circ + 150^\circ = 60^\circ$, and the third phase – to angle $\psi_{\mathrm{opt},C} = -90^\circ + 240^\circ = 150^\circ$. Usually first and second phases energize simultaneously when reference signal angle is 60° [8].

Table 1 - Optimal energizing phases of shunt reactor

Windings connection	**Number of magnetic core limbs**	**Phase A**	**Phase B**	**Phase C**

Star with grounded neutral	4 or 5	90°	210°	330°
	3	90°	$90^\circ - \arg\left(e^{-j120^\circ} + k_m\right)$	330°
Star with isolated neutral	3–5	60° (phases A and B are energized synchronously)		150°
Delta				
Star with neutral grounding reactor	4 or 5	90°	$90^\circ - \arg\left(e^{-j120^\circ} - \frac{k_n}{k_n + 1}\right)$	330°
	3	90°	$90^\circ - \arg\left(e^{-j120^\circ} - \frac{k_n - k_m}{k_n + 1}\right)$	330°

Evaluation of circuit commutation instant

During switching process, controlled switching device monitors process parameters such as electrical and breaker contacts mechanical closing instants. These parameters are used to assess a success of switching procedure and to monitor changes of high-voltage circuit breaker characteristics during the time of operation. On the basis of data obtained during previous commutation an adaptive correction in estimation of breaker closing time is made. This correction takes into account deviations of actual operating time from expected value.

In order to determine electrical circuit closing time controlled switching devices estimate actual commutation moment. In modern devices the commutation moment is determined by detection of current emergence in reactor circuit. To obtain high time resolution, the current signals are recorded with high sampling rate (up to 10 kHz), which is much higher than the sampling rate of typical intelligent electronic devices used for relay protection and automation purposes. Therefore, implementation of controlled switching function in intelligent electronic devices requires installation of auxiliary equipment.

A new method for evaluation of actual energizing moment was first proposed by authors in [9]. The method based on dependence (6) which establishes relationship between free component amplitude of reactor current I_{fr} and commutation phase. The method accuracy depends on estimation precision of free component initial value and amplitude of steady-state component in reactor current. High precision estimation of this parameters is provided by adaptive structural analysis method [10].

A digital structural model

$$a_0\hat{x}(k) = -\sum_{m=1}^{M} a_m x(k-m)\,, k \geq M, \tag{10}$$

used as a tool for recognizing a signal structure in adaptive structural analysis [11]. The expression in (10) $a_0\hat{x}(k)$ is weighted with coefficient a_0 estimation of current signal sample $x(k)$, a_m is desired coefficients of structural model, $M \geq 3$ is order of model. The coefficient a_0 is chosen voluntary, usually $a_0 = 1$.

From coefficients a_m of structural model (10) characteristic polynomial is formed

$$P_M\left(\underline{\zeta}\right) = -\sum_{m=0}^{M} a_m \underline{\zeta}^{-m},$$

whose roots determine frequencies ω_i and damping coefficients α_i of signal components:

$$(\alpha_i + j\omega_i)T_s = \ln \underline{\zeta}_i.$$

Here T_s is a sampling interval.

The complex amplitudes of signal components are determined from signal component model which formed for elements of structural model effective core. In our case, the model will be as follows:

$$\hat{x}(k) = s\cos(k\omega T_s) + c\sin(k\omega T_s) + I_{\mathrm{fr}}e^{-k\alpha T_s},$$

where $c = I_{\mathrm{st}}\cos\psi$ and $s = I_{\mathrm{st}}\sin\psi$ are cosine and sine orthogonal components of signal respectively.

The amplitude of steady-state component is equal to

$$I_{\mathrm{st}} = \sqrt{c^2 + s^2}.$$

The actual switching phase of shunt reactor is estimated from obtained values I_{fr} and I_{st} and according to equation (6) (Figure 5).

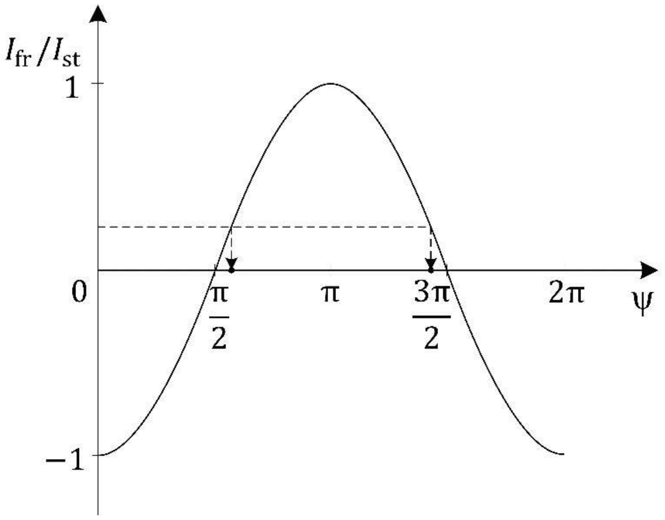


Figure 5 - Relationship between ratio of current free component initial value I_{fr} to amplitude of current steady-state component I_{st}, and phase ψ of supply voltage at shunt reactor energizing instant

To study the properties of proposed method, a simulation model of power network is developed in Simulink (Figure 6). Electrical system is represented as an EMF source with active-inductive impedance and capacitive shunt connected to earth. The windings connection scheme of shunt reactor in model is a star with grounded neutral; the windings are represented by RLC-equivalent circuits.

The spread of operating time of modern high-voltage circuit breakers does not exceed 2 ms (36°). Therefore, modeling focuses on study of switching phase estimation errors in range of switching phases from 54° to 126°.

Table 2 shows change ranges of equivalent circuit parameters used for modeling [4, 12].

Table 2 – Parameters of equivalent circuit

Equivalent circuit element	Resistance R, Ohm	Inductance L, H	Capacity C, nF
Reactor	$(0.0017 \div 0.0036)X_R$	$1.4 \div 10.35$	$1.3 \div 4.1$
System	$L_S + L_R$	0.05	$10C_R$

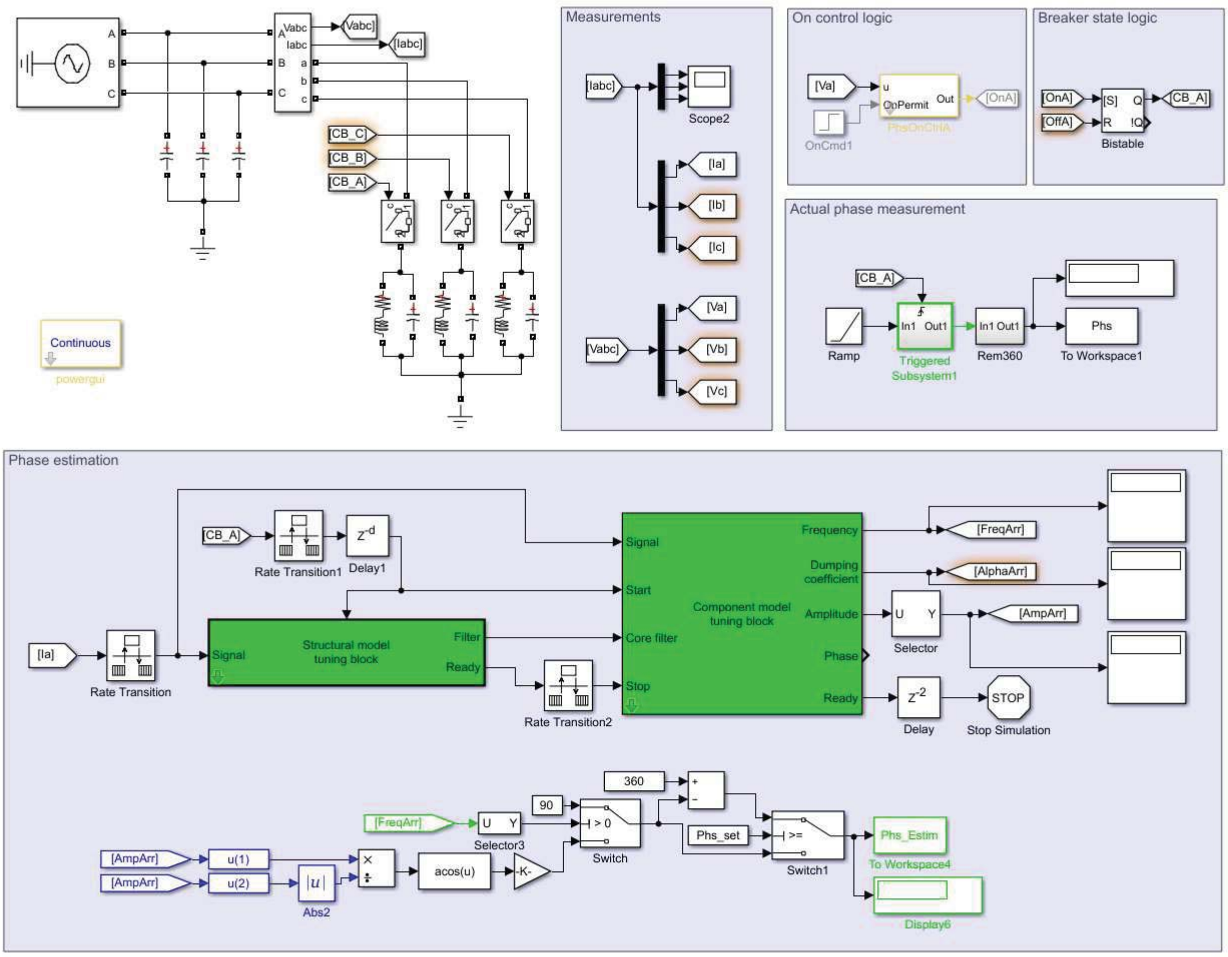


Figure 6 - Shunt reactor energizing model in Simulink

Simulation expected shows that estimation error of actual switching time reaches a maximum in case of minimum inductance and maximum active resistance and capacitance of shunt reactor. This is explained by the fact that in this case parameters of scheme are significantly different from algorithmic model used by the method. In range of switching phases from 54° to 126° the maximum switching phase estimation error of proposed method is relatively small and does not exceed 0.4 ° (0.022 ms).

Thus, the proposed method provides high accuracy estimation of shunt reactor energizing time without increasing of ADC sampling frequency of relay protection and automation intelligent electronic devices.

Conclusion

1. The universal approach to analysis of energizing processes of all types three-phase reactors based on representation shunt reactor with equivalent circuit in the form of star with neutral grounding reactor scheme.

2. It is convenient to analyze the processes during shunt reactor energizing using reduction scheme to zero initial conditions. Considering that controlled switching principle gets rid of free component in reactor current, the analysis of controlled switching can be performed in steady-state circuits.

3. Structural analysis of reactor current makes possible to increase estimation accuracy of shunt reactor energizing instant, and to implement controlled switching function in relay protection and automation intelligent electronic devices.

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