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Full Length Research Paper

Simple identification of a parallel resonance transfer function in power systems using a frequency response technique

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This paper proposes frequency response based identification of a parallel resonance transfer function in power systems including capacitor banks for power factor improvement. The proposed method is simple and easy to understand by finding undetermined coefficients. Only magnitudes of measured harmonic currents for some orders of both source and load are required. Validation of the proposed method is given in frequency domain and time domain by Bode plots and current waveforms, respectively. Simulation and experimental results are in good agreement. The proposed method is useful for a controller design of an active power filter in anti-parallel resonance.

Key words: Transfer function, identification, parallel resonance, harmonic, frequency response.

INTRODUCTION

With increasing nonlinear loads associated with harmonics such as solid-state converters serving as energy conversion for various applications like adjustable speed drives, power supplies, power controller, etc., a decreasing power quality is seriously concerned (Saxena et al., 2014; Han et al., 2014; Nojeng et al., 2015; Yingkayun et al., 2012). Harmonic currents and harmonic voltages cause additional losses in motors, transformers, power cables and so on. In case of a serious problem sensitive loads may be damaged. Harmonic currents cause a severe problem such as resonance. In power systems with power factor improvement using capacitor banks, if the frequency of load harmonic current is in the range of resonant frequency of the system, the source harmonic current is magnified. This is so called parallel resonance (Xu et al., 2005; Chaladying et al., 2015). As a consequence, equipment in the power system may be malfunctioned and damaged. Methods to prevent such problem are installations of either an active filter or a passive filter. The detuned passive filters (Kennedy et al., 2000; Detjen et al., 2001) consist of an additional inductor connected in series with the capacitor bank to shift resonance frequency of the power system away from the critical load harmonic current frequency. Disadvantages of this method are that when the system parameters change, redesign and reinstallation are required for the

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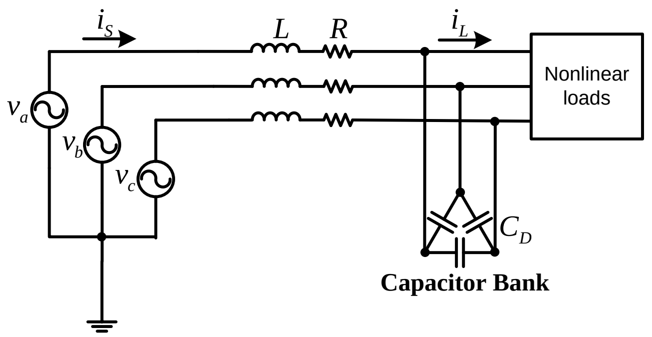
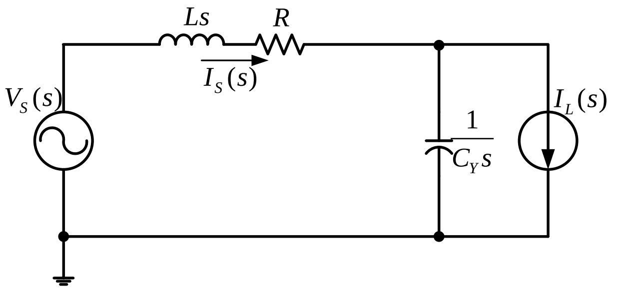


a. Three-phase power system



b. per-phase *s*-domain equivalence circuit

Figure 1. Power system with power factor correction using a capacitor bank.

changed resonance frequency. On the other hand, the active power filter is used for anti-parallel resonance (Kuo et al., 2007; Fang et al., 2009; Detjen et al., 2001; Wu et al., 2004; Jintakosonwit et al., 2007). The controller for the active filter can be designed to be robust for a variation of the system parameters. This method requires a transfer function of parallel resonance for the controller design.

In finding the transfer function of any system, there are 2 methods. The first method is based on a mathematical model using all known parameters of the system (Ogata, 1997). The second one is parameter identification with measured signals or known as empirical which is applied for this paper. Many methods for system identification such as genetic algorithms (Megherbi et al., 2010; Aliprantis et al., 2006; Biao and Yanliang, 2014), particle swarm optimization (Castillo et al., 2013; Li et al., 2011; Rashag et al., 2011), neural network (Wang and Chen 2006; Hsu et al., 2005; Hakim and Razak, 2011) are artificial intelligence identification. However, parameters tuning for the GA such as crossover, mutation, selection, fitness function, etc, which are tuned in order to get best solution, is trial and error. In particle swarm optimization algorithm, the disadvantages are that it is easy to fall into local optimum in high-dimensional space and has a low convergence rate in the iterative process (Li et al., 2014). The neural network needs many data points of input and output for training to achieve a correct solution which is a drawback of this method.

However, if we need a method which is not complicated, uses nominal data point of signal input and a well-known method, a frequency response technique (Nise, 2004) could be alternatively appropriate. Furthermore, the parallel resonance transfer function is on the basis of frequency response. Therefore, this paper proposes the parallel resonance transfer function identification in power systems using the frequency response technique. The paper is organized as follows. Firstly, mathematical modeling is presented for explaining parallel resonance in a power system. Next, the equations and procedure of the proposed identification of the parallel resonance transfer function is given in this section. Then, the parallel resonance transfer function is identified and verified. Finally the conclusion is given.

MATHEMATICAL MODELING

This section describes a mathematical model for determining the parallel resonance transfer function. A three-phase power system with nonlinear loads and power factor correction is represented with a per-phase equivalent circuit. As a consequence, the parallel resonance equivalent circuit is achieved.

Power system diagram

A three-phase power system with power factor correction using a capacitor bank is shown in Figure 1. It consists of a three-phase source (v_a, v_b, v_c), source inductance L, source resistance R, delta-connected capacitor bank and nonlinear loads. The purpose of this paper is to find out the transfer function of the parallel resonance in *s*-domain. It is necessary to use Laplace transform for the power circuit in Figure 1(a) resulting in *s*-domain circuit as shown in Figure 1(b). Per-phase reactive power compensation capacitance is given as:

$$C_Y = 3C_D \tag{1}$$

C_Y is star-connection equivalent capacitance. $V_S(s)$, and $I_L(s)$ are per-phase Laplace transform variables of source voltage v_a, source current i_S and load current i_L, respectively.

Parallel resonance transfer functions

When considering only an effect of the load current $I_L(s)$ on the source current $I_S(s)$, a parallel resonance equivalent circuit can be illustrated in Figure 2 derived from Figure1(b). Form Figure 2, a transfer function which demonstrates the relation between $I_L(s)$ and $I_{SL}(s)$, can be obtained as follows:

$$I_{SL}(s) = \frac{\frac{1}{C_Y s}}{Ls + R + \frac{1}{C_Y s}} I_L(s) \tag{2}$$

$$G_M(s) = \frac{I_{SL}(s)}{I_L(s)} = \frac{1}{LC_Y s^2 + RC_Y s + 1} \tag{3}$$

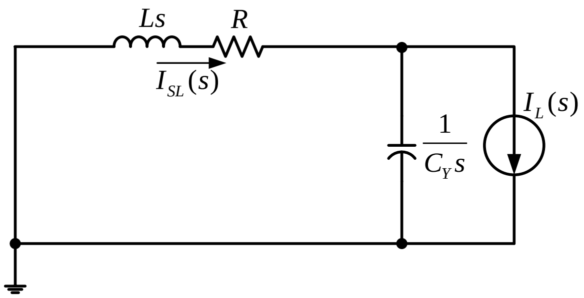


Figure 2. Parallel resonance equivalence circuit

Table 1. System parameters.

Parameters	Values
Capacitor (C_Y)	$21\mu\text{F}$
Source inductance (L)	$8.2\,\text{mH}$
Source resistance (R)	1.8Ω

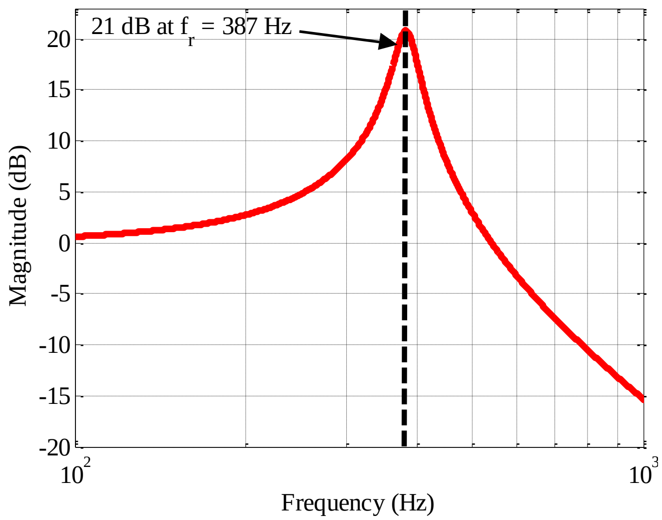


Figure 3. Amplitude-frequency characteristic of $G_M(s)$

Where $G_M(s)$ is a mathematical parallel resonance transfer function. In order to show frequency response of the parallel resonance, substituting circuit parameters in Table 1 obtained from the measurement into equation (3) gives:

$$G_M(s) = \frac{1}{1.722\times10^{-7}s^2 + 3.78\times10^{-5}s + 1} \tag{4}$$

Bode diagram which demonstrates a magnitude of $G_M(s)$ is shown in Figure 3. In Figure 3, as can be seen, the peak magnitude of frequency response is 21 dB at frequency of 387 Hz of which this frequency is called resonance frequency f_r. The resonance frequency can be calculated from:

$$f_r = \frac{1}{2\pi\sqrt{LC_Y}} \tag{5}$$

From Figure1b, the source current $I_S(s)$ can be obtained by applying the supper position theory as:

$$I_S(s) = I_{SL}(s) + I_{SV}(s) \tag{6}$$

Where $I_{SV}(s)$ is the source current resulting from the voltage source (see Appendix). This equation (6) will be used to confirm the correctness of the identified parallel resonance transfer function in the next section.

PARALLEL RESONANCE TRANSFER FUNCTION IDENTIFICATION

The transfer function identification of the parallel resonance in this paper is based on a frequency response technique (Nise, 2004). In the previous Section, it can be seen that the mathematical parallel resonance transfer function $G_M(s)$ is a second order system. Therefore, the identified parallel resonance transfer function, $G_I(s)$ is also defined as a second order system as

$$G_I(s) = \frac{1}{Xs^2 + Ys + 1} \tag{7}$$

where X and Y are coefficients of s^2 and s, respectively. By comparing between the equations (7) and (2), it can be seen that $X = LC$ and $Y = RC$. The frequency response of $G_I(s)$ is achieved by substituting $s = j\omega$ in the equation (7). It can be written in the following form:

$$G_I(j\omega) = \frac{1}{X(j\omega)^2 + Y\omega j + 1} \tag{8}$$

Where ω is an angle frequency (in radians per seconds). The magnitude of $G_I(j\omega)$ that is a current gain a can be obtained as:

$$a = \left|G_I(j\omega)\right| = \frac{1}{\sqrt{(1 - X\omega^2)^2 + (Y\omega)^2}} \tag{9}$$

By reformatting the aforementioned equation to a general standard equation, it can be expressed as:

$$(1 - X\omega^2)^2 + (Y\omega)^2 = \frac{1}{a^2} \tag{10}$$

Where

$$a = \frac{I_{SLh}}{I_{Lh}} \tag{11}$$

I_{SLh} and I_{Lh} are RMS values of individual harmonic currents of the source and load, respectively, which are measured from the experimental setup.

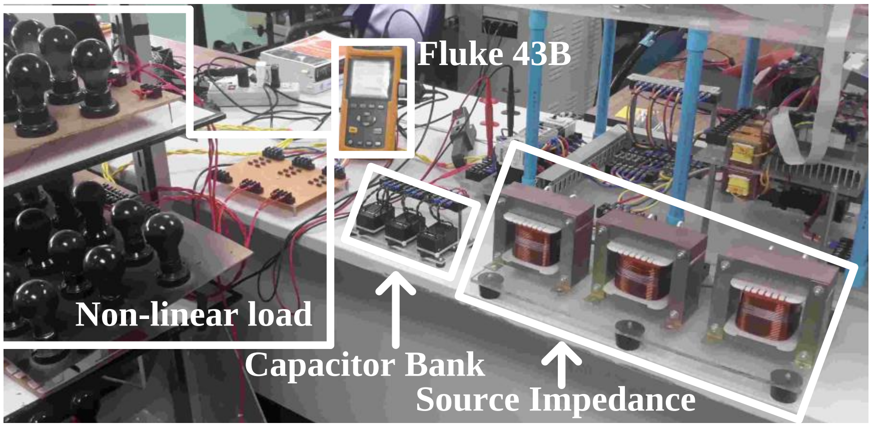


Figure 4. Photograph of hardware implementation

Equation 10 is a two-variable equation. Therefore, it needs two equations to solve for X and Y. Measured I_{SLh} and I_{Lh} with two significant harmonic orders of which I_{SLh} are most amplified in the range of resonance. In this paper, harmonic orders which are most amplified are 5th-order harmonic (250 Hz) and 7th-order harmonic (350 Hz). Then, measured rms harmonic currents of such order of the source and load are used to substitute in the equations 11 and 10. After that, the equation 10 is solved for evaluated X and Y. Finally, the identified parallel resonance transfer function $G_I(s)$ is obtained by substituting X and Y into the equation 7. Detail for parallel resonance transfer function identification will be demonstrated in the next section.

RESULTS

This section includes 2 parts. In the first part, the equation 10 is applied for the parallel resonance transfer function identification in frequency domain and the results of the first part will be verified in the second part for the time domain.

Identification

This section gives descriptions of an experimental setup and testing for determining the parallel resonance transfer function. Figure 4 shows the experimental setup including a three-phase four wire 400 V, 50 Hz supply, three-sets of inductors representing source impedance, a three-phase diode bridge rectifier supplying pure resistors acting as nonlinear loads and capacitor banks. The source impedance and reactive power compensation capacitance are shown in Table 1. The harmonic currents are measured by a Fluke 43B power quality analyzer.

Procedure for identifying the parallel resonance transfer function commences with measuring load current and source. Current waveforms are shown in Figure 5a (below trace) and Figure 5c (below trace), respectively. Corresponding harmonic spectra are shown in Figure 5b and d, respectively. The rms value of each harmonic current of the load current and the source current and the current gain (that is, equation 11) is shown in Table 2. Then, substituting the data of 5th and 7th harmonic order of Table 2 into equation 10 gives the following equations.

For 5^{th} harmonic order:

$$\left(1-X\left(2\pi(5)(50)\right)^2\right)^2+\left(Y\left(2\pi(5)(50)\right)\right)^2=\frac{1}{1.712^2} \qquad (12)$$

For 7^{th} harmonic order:

$$\left(1-X\left(2\pi(7)(50)\right)^2\right)^2+\left(Y\left(2\pi(7)(50)\right)\right)^2=\frac{1}{1.712^2} \qquad (13)$$

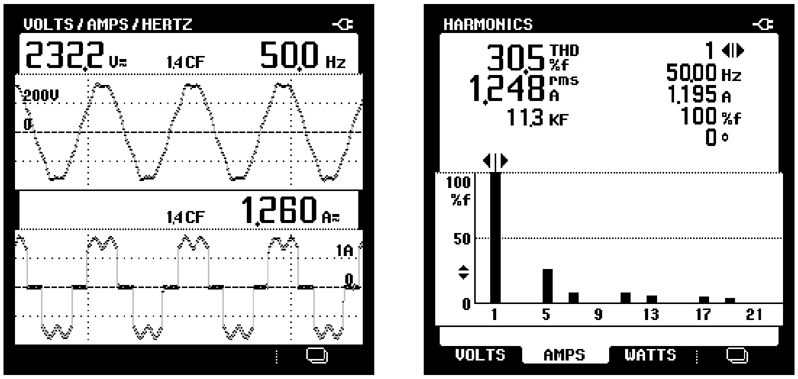
Solving the equations 12 and 13 to find X and Y variables yields:

$$\begin{aligned}
&A_1:\{X=-1.698\times10^{-7}, Y=-8.235\times10^{-4}i\}\\
&A_2:\{X=-1.698\times10^{-7}, Y=8.235\times10^{-4}i\}\\
&A_3:\{X=\ 1.698\times10^{-7}, Y=-3.526\times10^{-5}i\}\\
&A_4:\{X=\ 1.698\times10^{-7}, Y=3.526\times10^{-5}\}
\end{aligned} \qquad (14)$$

There are 4 solutions which are A_1, A_2, A_3 and A_4. From equation 7, it can be seen that X and Y variables are both positive coefficients. Therefore, the correct solution is A_4. Finally, the identified parallel resonance transfer function $G_I(s)$ can be obtained as follows:

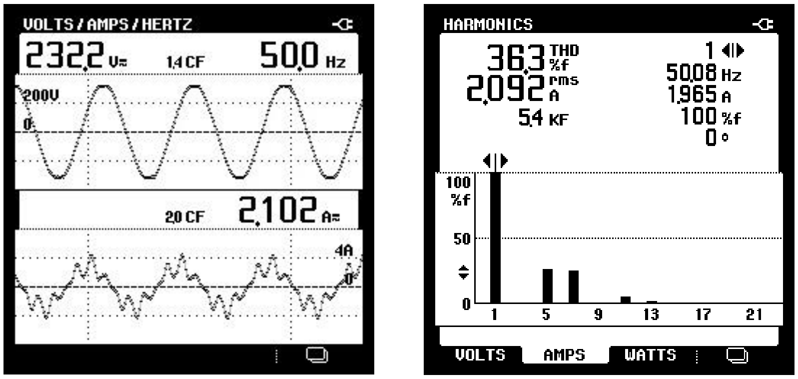
$$G_I(s)=\frac{1}{1.698\times10^{-7}s^2+3.526\times10^{-5}s+1} \qquad (15)$$

Figure 6 illustrates a comparison between frequency



(a) Waveforms of load voltage (above) and load current (below)

(b) Harmonic spectrum of load current



(c) Waveforms of source voltage (above) and load current (below)

(d) Harmonic spectrum of source current

Figure 5. Waveforms and spectra of the signals.

Table 2. Load current, source current and current gain of each harmonic order.

Parameter	**Harmonic order**					
	5					

Parameter	**5th**	**7th**	**11th**	**13th**	**17th**	**19th**
I_{SLh} (A)	0.512	0.486	0.100	0.040	0.012	0.007
I_{Lh} (A)	0.299	0.095	0.096	0.072	0.064	0.049
a	1.712	5.116	1.042	0.556	0.187	0.143

response magnitudes of $G_M(s)$, $G_I(s)$ and experimental results (i.e. $20\log(a)$). It can be seen that they are in a good agreement. However, the experimental results at the 17th and 19th harmonic frequency is slightly different from those for $G_M(s)$ and $G_I(s)$. This could be the difficulty in the accurate measurement of small magnitudes of the higher harmonic order. According to the compared results, the proposed method provides the best representation of parallel resonance since the frequency response is in accordance with others.

Verification

In order to verify the correctness of the identified parallel resonance transfer function $G_I(s)$ achieved from the previous section, a comparison in time domain between source current waveforms for experiment, power system simulation and the proposed method. The power system

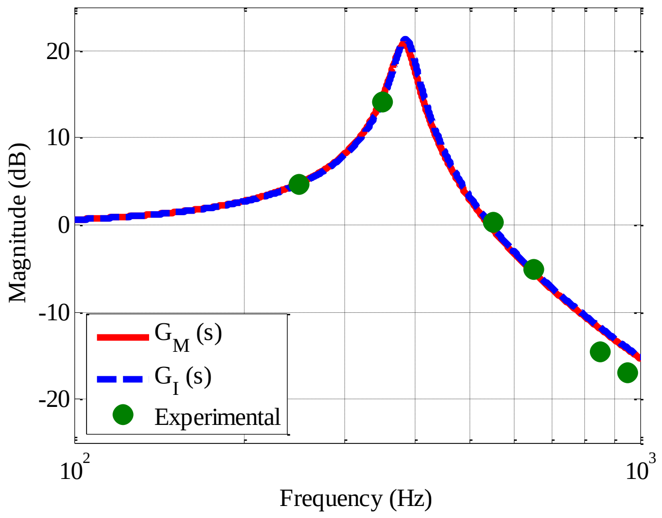
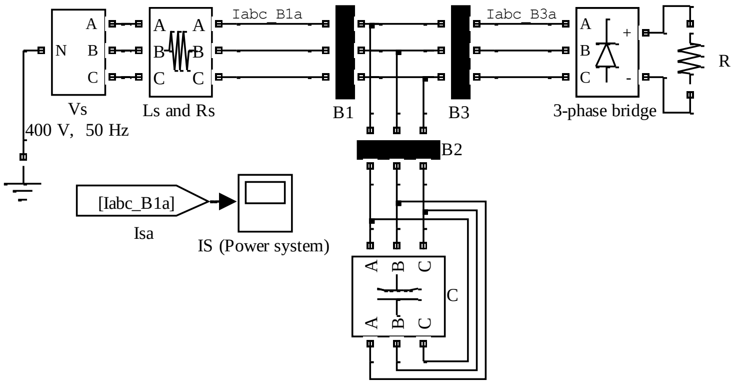
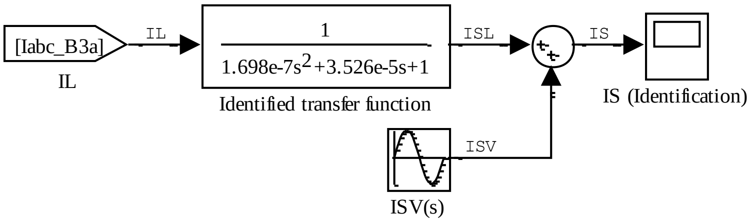


Figure 6. Magnitude of $G_M(s)$, $G_I(s)$ and experimental results in dB versus frequency



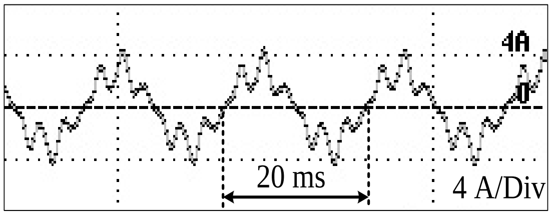
(a) Power system simulation diagram



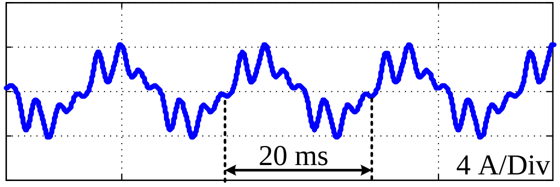
(b) Identified transfer function simulation block diagram

Figure 7. Simulation diagram for verification

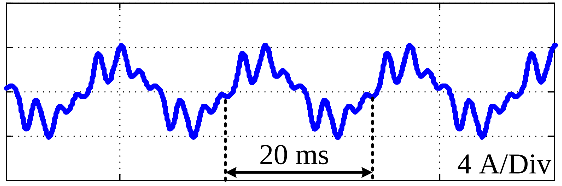
simulation diagram is shown in Figure 7a using the parameters in Table 1. The identified transfer function simulation is shown in Figure 7b using the equation 6 (that is, superposition). I_{SL} is the output of the block of the identified transfer function which the nonlinear load current I_L is input coming from Figure 7a whereas the source current I_{SV} is calculated as shown in Appendix. Figure 8 shows a comparison of time response between



(a) Experimental result



(b) Power system simulation result



(c) Identified transfer function simulation result

Figure 8. Time response of source current

experimental results, power system simulation and identified transfer function which all results are almost identical. Therefore, according to these results, the proposed method is an alternatively appropriate method for parallel resonance transfer function identification.

Conclusion

This paper has proposed simple identification of a parallel resonance transfer function based on frequency response in power systems including capacitor banks for power factor improvement. Initially, a mathematical model of parallel resonance transfer function which is a second order system is created with the known parameters. Procedure and equations for finding parallel resonance transfer function is described. Results of the identified parallel resonance transfer function are compared in magnitude (system gain) with the mathematical model and experimental results in frequency domain on Bode diagram and it is simulated to compare with power system simulation and experimental results in time domain. Both frequency domain and time domain simulation results are demonstrated to show that the proposed method is an alternatively appropriate method for parallel resonance transfer function identification.

Conflict of Interests

The authors have not declared any conflict of interests.

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Appendix

The source current resulting from the voltage source $I_{SV}(s)$ can be derived in:

$$I_{SV}(s) = \frac{V_S(s)}{Ls + R + \dfrac{1}{C_Y s}} \qquad \text{(A1)}$$

$$G_{SV}(s) = \frac{I_{SV}(s)}{V_S(s)} = \frac{C_Y s}{LCs^2 + RCs + 1} \qquad \text{(A2)}$$

Where $G_{SV}(s)$ is a transfer function which the source affects the source current. For 50 Hz ($\omega = 314.16$) and from the system parameters in Table1, it can be calculated as:

$$= \frac{(21\times10^{-6})(j314.16)}{(8.2\times10^{-3})(21\times10^{-6})(j314.16)^2 + (1.8)(21\times10^{-6})(j314.16) + 1} \; G_{SV}(j314.16) = \frac{j6.6\times10^{-3}}{0.983 + j11.9\times10^{-3}} \qquad \text{(A3)}$$

$$= 0.0067\angle 89.3^o$$

Finally, $I_{SV}(s)$ can be obtained as follows:

$$I_{SV}(s) = G_{SV}(s)V_S(s) = (6.7\times10^{-3}\angle 89.98^o)(230\sqrt{2}\angle 0^o)$$

$$I_{SV}(s) = 2.18\angle 89.3^o \qquad \text{(A4)}$$

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