Generator Excitation Systems Sensitivity Analysis and Their Model Parameter's Reduction

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Abstract— **Since power systems have large scale, nonlinear parameters, including uncertainty, researchers have presented many methods for model simplification. Voltage dip and transients are known for their importance in dynamic studies and as a result of short circuits or starting a large induction motor, generator excitation systems come into effect in order to compensate voltage oscillations and voltage dips during such transients. This paper will address model parameter reduction of generator excitation systems. An objective function and a simple method for sensitivity analysis will be proposed to identify which excitation parameters are more sensitive and have more impact on generator voltage response. Moreover, the proposed method can be used to determine which parameters do not have significant effect on the excitation system. The objective function will stress voltage dip and overshoot rather than small oscillations and transients. A small stand-alone micro gird, with three induction motors and a generator with IEEE ST2A excitation system have been selected to simulate and verify the method performance.**

Index Terms-- Sensitivity Analysis, Model Order Reduction, Electrical Distribution System (EDS), Excitation System, Micro Grid and Island Operation.

I. INTRODUCTION

Over the past few decades, many simulation programs have been developed in order to model, design, and analyze large Electrical Distribution Systems (EDS). One of the features of simulation software is dynamic modeling and analysis of the power system to reflect the actual system responses. In general, to have an accurate EDS model, many parameters and their related data must be gathered and considered. However, in some parts of a model, there is no need to have all parameters in order to perform an accurate simulation. For instance, among all of the generator excitation system parameters, only several may impact the generators voltage response behavior.

Sensitivity Analysis could be utilized and useful to find out how parameters and uncertainties will affect the output, test the robustness of a model or system, and understand the relationship between inputs and outputs. Likewise, sensitivity analysis is useful for model simplification and order reduction since some parameters, in every system, do not have any meaningful impact on the outputs.

This paper will address sensitivity analysis to simplify the model of an exciter and identify which parameters will have more influence on the output voltage response specifically. For this study, the IEEE type ST2A excitation system model and Electrical Transient Analyzer Program (ETAP) as the simulation software are selected.

Hiskens and Pai in [1] examined the tools and methods to study the application of sensitivity analysis for linearization of a large power system around its trajectory not equilibrium point. Many papers have been published regarding power system's eigenvalue sensitivity. Designing and locating controllers in large power systems can be simplified by eigenvalue sensitivity analysis, which provides important and useful information for optimizing controller parameters [2]. Traditional methods of eigenvalue sensitivity in power systems have been proposed in [3], [4].

Various methods of sensitivity analysis and its application in a broad range of fields are presented in [5].

Located in section II of this paper, the problem statement is described and some basics related to voltage dips and transients are discussed. Next, a small scale power system in island operation (i.e. micro grid) is selected and discussed for this analysis. Furthermore, in the last part of section II, ST2A is introduced as an excitation system. In section III, a sensitivity analysis method for model simplification is proposed. In section IV, the proposed method is applied to the system case study and results are discussed. Conclusions and future work are mentioned in section V.

II. PROBLEM STATEMENT

A. *Voltage Dip: concept and basics*

Since voltage response is one of the main concerns of electrical engineers, studies of voltage dips have increased. A significant drop in voltage profile is known as voltage dip or voltage sag. Damages caused by voltage dips on network equipment or customer devices have some economic impacts for operators. A large amount of current draw in one part of the system may result in voltage dip from a fault or starting of

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a large motor. Each voltage dip has two main characteristics, the magnitude and the duration of the voltage response.

According to IEEE standard 1159-1995 [6], magnitudes of voltage dips (in rms) are defined as 0.1 to 0.9 per unit. Also voltage dips last from 0.5 cycles (10ms for 50 Hz systems and 8ms for 60 Hz systems) to 1 minute. Dip duration can be divided into three categories as follows:

Instantaneous	1/2 cycle to 30 cycles
Momentary	30 cycles to 3 Seconds
Temporary	3 Seconds to 1 Minute

A voltage drop which lasts more than 1 minute is considered an Undervoltage; if it lasts less than 0.5 cycles it is known as a Transient. However, voltage greater than 1.1 per unit, which takes from 8ms to 1 minute, is called a voltage swell.

Voltage Dips and Swells can undesirably trip sensitive controllers, actuators, and protective relays. Other devices and equipment which can be damaged by voltage dips or swells are included, but not limited to, induction motors, synchronous motors, Variable Speed Drives, Programmable Logic Controllers, and computers [7].

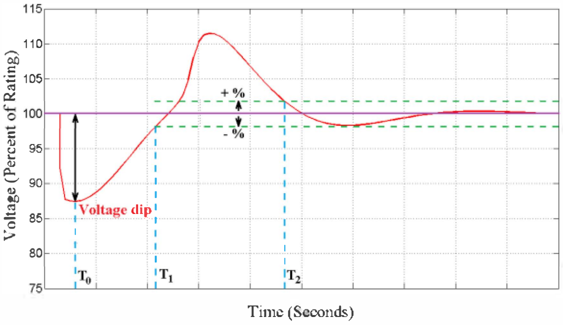

Figure 1. Voltage dip and overshoot in a voltage step response

T_0 is the time of the motor acceleration and the starting time of voltage drop, T_1 is when voltage recovers to the steady state, and T_2 is when voltage overshoot settles back to the steady state boundary.

Starting large induction motors in island mode is one of the causes of voltage dip. In this scenario, due to large reactive power consumed by motors at the startup, voltage dip and swell will occur. A momentary voltage dip will occur due to inrush current flowing into the motor during the motor acceleration. The size of the voltage drop is directly correlated to the size and model of the induction motor which is started. Further investigation on the motor model and its effects on the system voltage response revealed that the voltage dip at the beginning of this response is directly proportional to the motor locked rotor impedance parameter, consequently locked rotor current (LRC), and not the excitation system parameters in the network. The excitation system cannot regulate voltage to the design set point instantaneously.

Induction motor transient behavior is simulated by starting one 1000HP 6.6KV motor, Figure 5, with two different LRC, 625% and 750%. The motor circuit model is estimated utilizing the parameter estimation module in ETAP. Based on [9], parameter estimation is performed using the nameplate data along with two points from the motor performance curves. These two points include the locked rotor current (LRC) and breakdown torque. These parameters can be found from actual machine tests or from curves supplied by the manufacturer.

Figure 2. and Figure 3. show the estimated induction motor circuit model for these two cases.

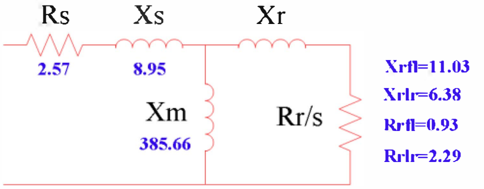

Figure 2. Induction Motor Model Estimated for LRC 625%

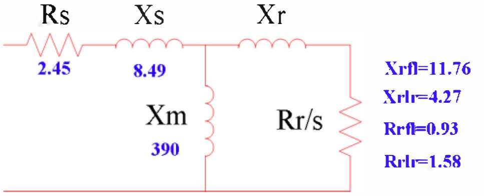

Figure 3. Induction Motor Model Estimated for LRC 750%

Figure 4. shows that increasing the LRC from 625% to 750%, will increase the voltage dip by 2.25% during accelerating period.

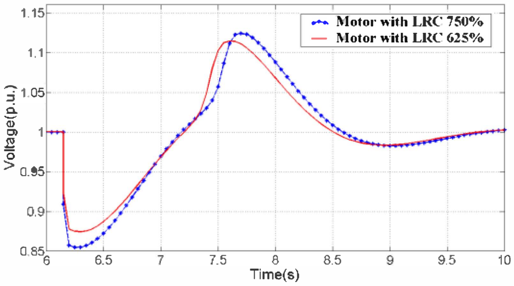

Figure 4. Terminal Voltage of Generator, in Figure 5, during the Motor Acceleration

B. Voltage Dip in Microgrids

Microgrids are a combination of interconnected loads with a distributed generator(s) that can be connected to the grid. When connected to the grid, it is called grid-connected mode; when disconnected from the grid, it is called island mode. Types of loads include static loads, UPS, motors driving pumps, fans, etc. Distributed generators can be standby diesel generator units, microturbines, solar panels, wind generators, fuel cells, etc. [10]. The voltage dip or swell can sometimes cause misoperation of protective relays. Since voltage drop cannot be modified by excitation system parameters, electrical engineers attempt to use an appropriate generator excitation system model and tune parameters in order to reduce duration of voltage dips. For this study, a small island distribution system with four loads is considered and shown in Figure 5.

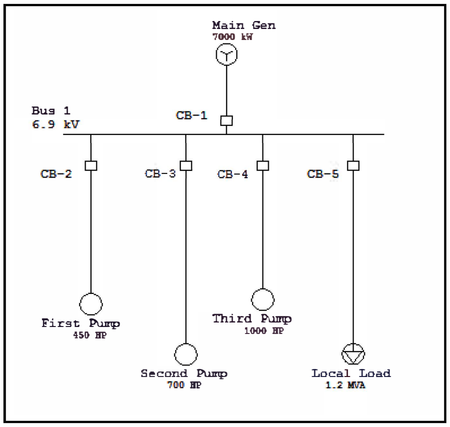

Figure 5. Schematic of a stand-alone microgrid

A preloading of 1.2 MVA is considered when starting three induction motors within different time periods. Figure 6. shows the voltage response at 6.9 kV Bus-1 during motors acceleration.

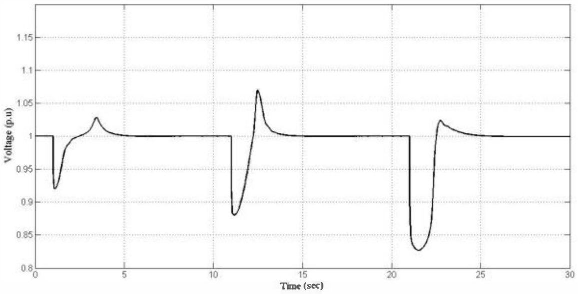

Figure 6. Voltage response for accelaration of three induction motors

C. *Excitation System*

Generators' dynamic voltage response behaviors are greatly affected by their excitation systems. Excitation systems have a great impact on the generator voltage profile and reactive power. IEEE excitation systems are categorized as AC type, DC type, and ST type. Functions and characteristics of different types of excitation systems are not the subject of this paper. However, a method for sensitivity analysis for various parameters of excitation systems is addressed here. IEEE type ST2A has been chosen as a test case for the sensitivity analysis.

This static excitation system uses both voltage and current sources to produce the excitation power. It uses an uncontrolled rectifier to create the DC source for the generator field [5]. Figure 7. shows the model of IEEE ST2A excitation system.

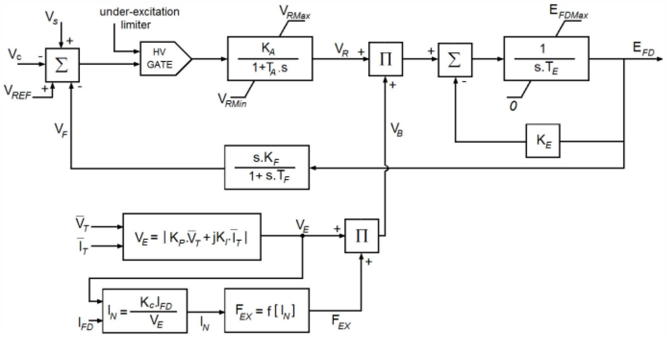

Figure 7. IEEE ST2A excitation system block diagram[6]

III. SENSITIVITY ANALYSIS

In order to find out how much each parameter can affect the output, an objective function should be defined. This sensitivity analysis can be done to simplify the complicated model of the exciter for further studies and calculations. For instance, due to nonlinearity and a complicated model of an excitation system, parameter identification is complex and not possible. Technically, having an accurate model with all of the parameters for such system is impractical. Therefore, by using measured data including inputs and outputs and applying system identification methods such as Recursive Weighted Least Square (RWLS), the mathematical model of the system can be derived. In this regard, more sensitive parameters will get more weight in comparison with other parameters in RWLS, WLS (Weighted Least Square), and other methods. On the other hand, less sensitive parameters can be considered as constants in order to reduce the size of unknown parameters.

There are many criteria which are used as a performance index. Integral of Absolute Errors (IAE) or Sum of Absolute Errors (SAE) is summation of the deviations between measured signal and expected signal. IAE and SAE are the same in concept; however, IAE and SAE are used for continuous signals and sampled signals, respectively. They can be defined as follows:

$$IAE = \int_{o}^{T_f} \left| y_{measured}(t) - y_{reference}(t) \right| \tag{1}$$

$$SAE = \sum_{t=0}^{T_f} \left| y_{measured}(t) - y_{reference}(t) \right| \tag{2}$$

Also, Integral of Square Errors (ISE) and Sum of Square Errors (SSE) are commonly employed as a criterion to be minimized. These indices penalize for larger errors rather than smaller ones.

$$IAE = \int_{o}^{T_f} \left(y_{measured}(t) - y_{reference}(t) \right)^2 \quad (3)$$

$$SAE = \sum_{t=0}^{T_f} \left(y_{measured}(t) - y_{reference}(t) \right)^2 \quad (4)$$

There should be an objective function to emphasize on different parts of the voltage response (Figure 1. Needless to say, voltage dips and swells need more weight in comparison with small steady state errors. In this regard, the following objective function is proposed:

$$J = \sum_{t=t_0}^{t_1} W_1 \left(y_{out(t)} - y_{ref(t)} \right)^2 + \sum_{t=t_1}^{t_2} W_2 \left(y_{out(t)} - y_{ref(t)} \right)^2$$
$$+ \sum_{t=t_2}^{t_3} W_3 \left(y_{out(t)} - y_{ref(t)} \right)^2 \quad (5)$$

Minimizing the objective function results in less error in voltage dips and overshoots, which means the system has less response time and more accurate voltage response. W1, W2, and W3 are weights, where W1 is greater than W2 and W2 is greater than W3. This means larger errors, specifically in voltage dips, are more important than other errors. Although the amount of voltage drop is directly related to the size and dynamic model of induction motors, the voltage dip duration can be decreased by modifying the excitation parameters.

There are two common analytical sensitivity functions, the absolute sensitivity function and the relative sensitivity function [5].

D. The Absolute Method

If we have the following function:

$$y = f(x_1, x_2, \ldots, x_n)$$

The absolute sensitivity function of y related to x_i is:

$$S_{x_i}^{y} = \frac{\partial y}{\partial x_i}\Big|_{OP} \quad (6)$$

Where OP stands for 'operating point' which means all variables have their normal values. Function f also can be time varying and partial differential should apply to y just with respect to x_i.

E. The Relative Method

In order to compare the effects of the parameters, the relative method can be more useful. The relative function is defined as follows:

$$S_{x_i}^{y} = \frac{\partial y}{\partial x_i}\Big|_{OP} \frac{x_i}{y} \simeq \frac{percent\ change\ in\ y}{percent\ change\ in\ x_i} = \frac{\Delta y / y}{\Delta x_i / x_i} \quad (7)$$

For our purpose, the relative method would be more appropriate. Figure 8. shows the algorithm for the sensitivity analysis for the excitation system parameters. By using this algorithm, we have two options, increasing or decreasing the parameters. If a parameter is sensitive, it would cause a large change in the objective function whether the parameter is increased or decreased. However, sometimes parameters are more sensitive in one direction. For example, when one parameter is increased, there is no impact on the output.

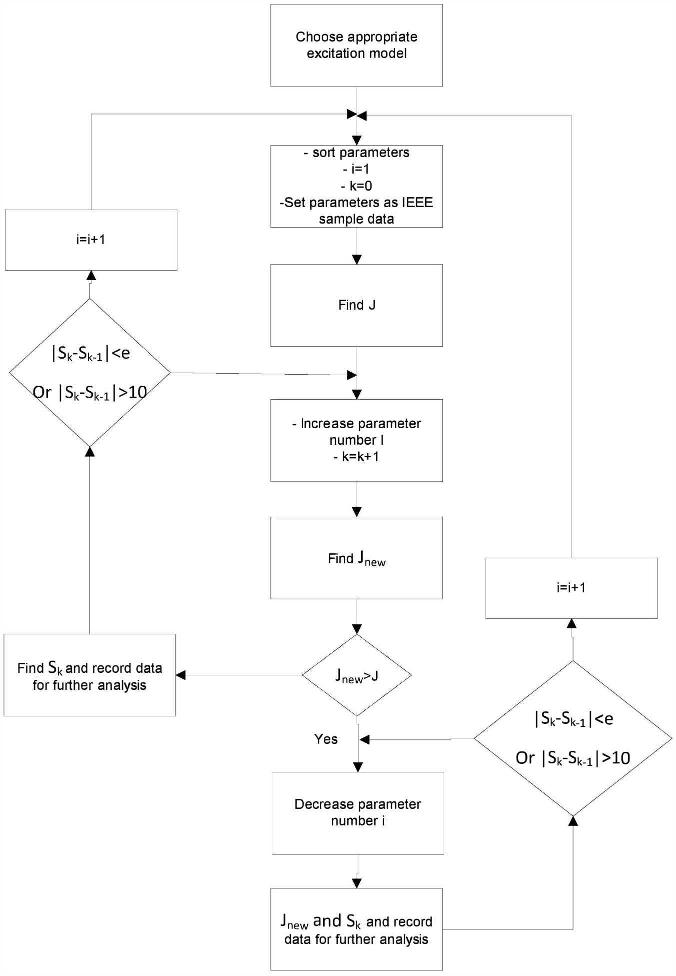

Figure 8. Sensitivity analysis flow chart

However, it does not mean that the parameter is not sensitive because we do not see the impact of decreasing for that parameter. Nevertheless, most of the sensitive parameters show their sensitivity in both directions.

IV. SIMULATION RESULT

A simple stand-alone micro grid that was introduced in section II part B has been simulated in ETAP. For sensitivity analysis the largest induction motor was considred since it has more voltage dip. After running the model in ETAP, voltage responses are saved and utlizing Matlab code to find J and S_k from [5] and [7].

In this paper, IEEE ST2A is selected for the excitation system. Figure 7. shows block diagram of IEEE ST2A excitation system. Different parameters of ST2A and their initial values based on IEEE recommendation sample data are shown in table 1 [6].

V. TABLE I. ST2A PARAMETERS SAMPLE DATA

Parameter	Description	Value
Controllers parameters		
T_A	Voltage regulator time constant	0.15 sec
K_A	Voltage regulator gain	120
T_F	Damping filter gain	1 sec
K_F	Damping filter time constant	0.05
$V_{R\,MAX}$	Voltage regulator output limits	1
$V_{R\,MIN}$	Voltage regulator output limits	0
Exciter and rectifier		
T_E	Exciter time constant	0.5 sec
K_E	Self Excitation gain	1
K_P	Potential circuit gain	4.88
K_c	Rectifier loading factor	1.82
K_I	Current circuit gain coefficient	8

Table 2 shows the sensitivity index for the parameters of ST2A during starting motor scenario as discussed above. In this paper, parameters are divided into 4 groups:

- Very sensitive if $S_k > 0.25$
- Sensitive if $0.25 > S_k > 0.05$
- Medium Sensitivity if $0.05 > S_k > 0.01$
- Not sensitive if $S_k < 0.01$

TABLE II.OBJECTIVE FUNCTION FOR ST2A PARAMETERS

Parameter	$\lvert S_k \rvert$
Controllers parameters	
T_A	0.014
K_A	0.006
T_F	0.0095
K_F	0.021
Exciter and rectifier	
T_E	0.194
K_P	0.323
K_c	0.032
K_I	0.15

Some of the parameters like self excitation constant (K_E) are relatively constant and they were not considered for sensitivity analysis. According to Table 2, potential circuit gain (K_P) is the most sensitive parameter among ST2A parameters and this depends on the excitation circuit design. Figure 9 shows the voltage response for vaious amount of K_P.

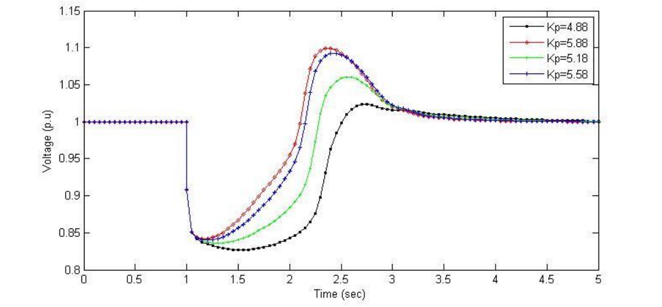

Figure 9. Voltage response with various K_Ps.

Exciter time constant (T_E) and current circuit gain coefficient (K_I) are sensitive (Figure 10).

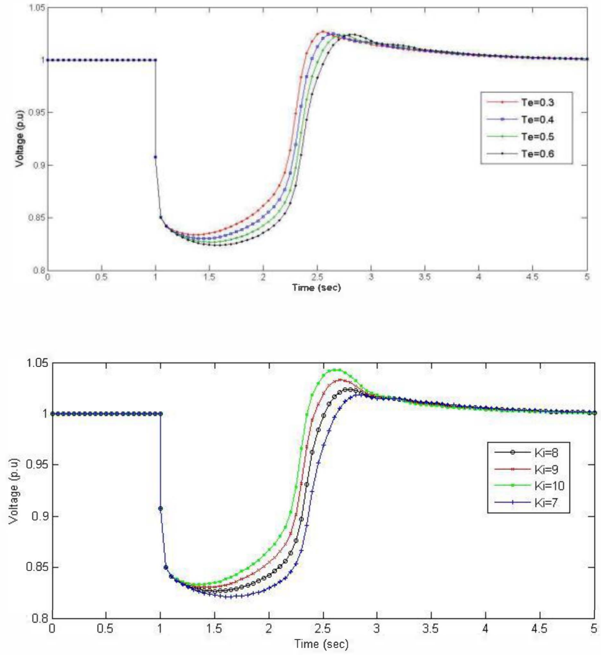

Figure 10. Sensitive parameters voltage response

Also, Rectifier loading factor ($\mathrm{K_c}$), Voltage regulator time constant ($\mathrm{T_A}$), and Damping filter time constant ($\mathrm{K_F}$) has medium sensitivity (Figure 11). Lastly, Voltage regulator gain ($\mathrm{K_A}$) and Damping filter gain ($\mathrm{T_F}$) are among non sensitive parameters (Figure 12).

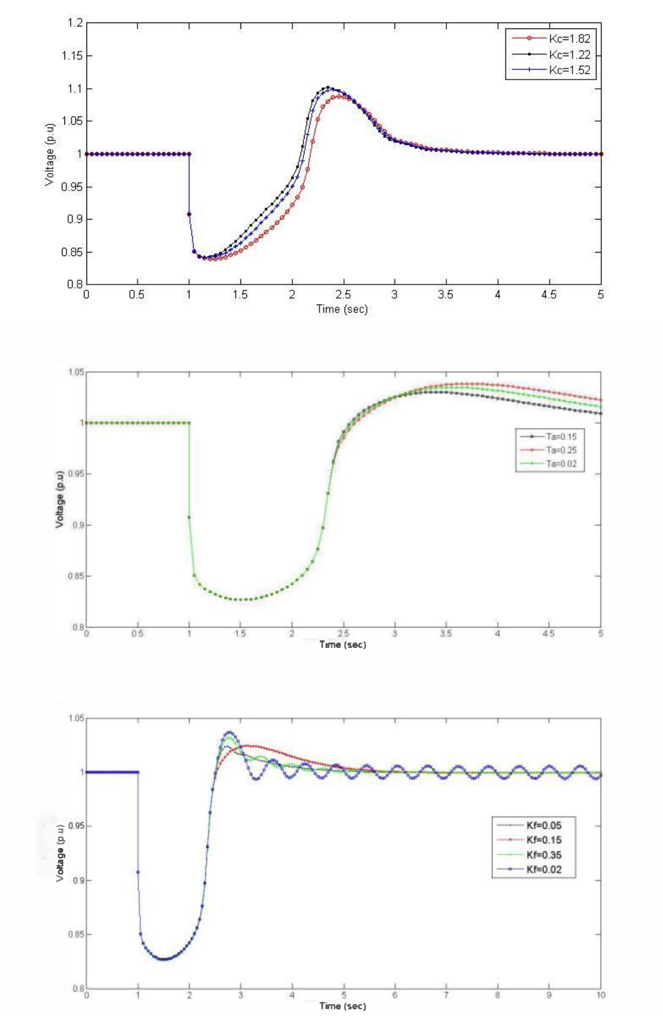

Figure 11. Medium sensitive parameters voltage response

VI. CONCLUSION

In this paper, we proposed a sensitivity analysis method to simplify a generator excitaion system based on voltage response. Stability analysis and voltage step response analyses need an accurate mathematical model of a system. The proposed sensitivity analysis method is useful not only for model simplification, but also for system identification which provides an accurate mathematical model. The proposed method is tested on IEEE ST2A excitation system with small scaled power system operating in an island mode micro grid. This method can be utilized in other excitation systems to evaluate its parameters sensitivity.

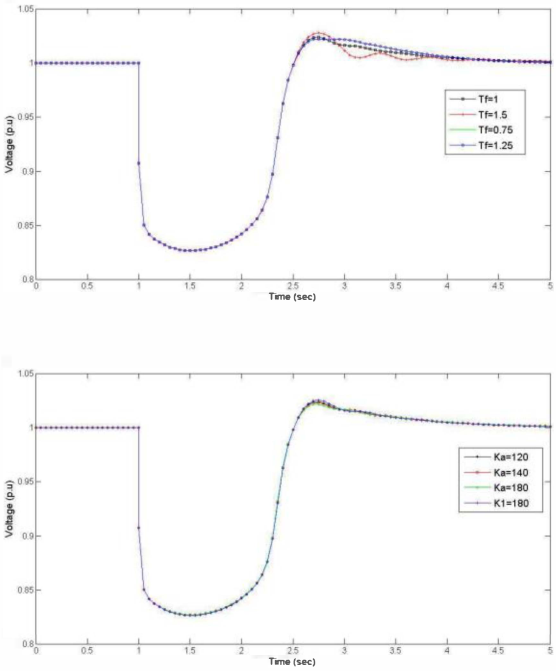

Figure 12. Non-sensitive parameters voltage response

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