Analysis of Power System Stability Using Prony Analysis

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***Abstract*— A good power system analysis is measured through the ability to detect response after experiencing disturbance within a specified requirement in a fastest way. In this manner, more condition can be implemented and analyzed to detect the possibility of instability that could lead to system collapse. Difficulty to detect the stability of a large power system network is due to simulation test produces up to thousands of output signal. Since the power system network grows each year, the simulation test of system stability should be performed each time the network changes in order to ensure the system adequacy and security are fulfilled. Furthermore, system stability test involves a lot of elements, where each of them need to be thoroughly examined, thus it is time consuming. This paper examines signal stability through its damping ratio, computes by a digital signal processing method named Prony analysis. Prony analysis will produces an output of amplitude, damping coefficient and frequency from an output signal as the components to calculate damping ratio. The calculation of damping ratio used as an indicator in achieving compliance with the limit specified by the Malaysian planning standards. Multiple software was used base on simulation and analysis among them are spreadsheet (Microsoft Excel), simulation (Power System Simulator for Engineer - PSSE) and analysis (MATLAB) are integrated together to dynamically screen several PSSE simulated output signal files consist of various elements at one instance to speed up analysis.**

***Index Terms*— amplitude, damping components, damping ratio, digital signal processing, frequency, MATLAB, Microsoft Excel, power system stability signal, Prony analysis, PSSE.**

I. Introduction

Fast detection of stability outputs are necessary in power system operation and planning industries in order to detect the irregularities of the system subsequent to the occurrence of disturbance. A good power system planner must cover as many possibilities in the analysis to prevent any power collapse. One of the major system collapse in Peninsular Malaysia occurred in 2003, where five states including Kuala Lumpur has a total of five hours power outage and costing the industries $13.8 million loss [1].

Damping ratio is one of the test that can measure the stability of a power system signal, provided that the ratio has to be above 5% for it to be considered as stable, in compliance with the Transmission System Reliability Standards (TSRS) sets by Malaysian grid owner. A digital signal processing (DSP) method named Prony analysis was adopted to calculate the signal's damping ratio from an individual elements in power system. Focusing on three power system elements of machine's rotor angle, bus voltage and bus frequency, each elements are assessed individually. The whole system is considered as unstable if any instability occurred in these signals.

A fast and accurate detection method has been developed using an integration of multiple software in order to analyze multiple output files, with combination of said elements at an instance. This method helps to speed up analysis by differentiating the stable signals with the unstable ones. Planners can spend more time focusing on the mitigation and rectification of unstable signals, by eliminating the stable ones.

Section II describes in much detail regarding the Prony analysis method used to calculate the damping ratio. Section III briefs on the integration of multiple software used in order to achieve more fast and accurate reading of signal's damping ratio based on the test signals produced. Results and discussion are presented in Section IV and Section V concludes the paper.

II. Prony Analysis

Digital signal processing (DSP) is a process of analyzing and modifying signal to optimize or improve its efficiency or performance [2]. Prony analysis is considered one of the DSP technique that produced worthy results in power system literature [3]. Prony analysis is an extension of Fourier analysis by directly estimating the frequency, damping and relative phase of modal components present in each signal [4]. Prony analysis has the advantage of estimating damping coefficients apart from frequency, phase and amplitude [5][6]. The usage of Prony analysis method is very significant to study the power system oscillatory dynamics signal, as it calculates the eigenvalue $(\sigma + j\omega)$ and eigenvector (amplitude and phase); which leads to damping ratio based on the equation (1).

$$\text{Damping ratio, } \zeta\ (\%) = \frac{-\sigma}{\sqrt{\sigma^2+\omega^2}}\ x\ 100\% \qquad (1)$$

A signal undergo Prony analysis will be extracted into several other signals based on the modal order number set, called Prony approximation signals. These signal are created based on four quantities; frequency, amplitude, phase, and damping coefficient. Each of the approximation signal produced its own frequency and damping coefficient value as in Fig. 1. The combination of Prony approximate signal, y[k] should be as close to the original measured signal, measured by the minimum squared error.

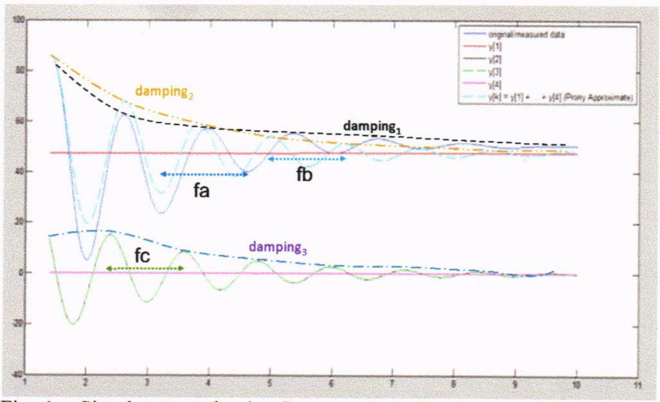

Fig. 1. Signal extracted using Prony analysis has its own frequency and damping coefficient value.

In Prony analysis, the modal order number must be identified. Usually in most real system, the modal order number is unknown, and there is no direct method to compute the modal order of a system. In [4], it is said that a good rule of thumb is to assume a modal order to be approximately one-third of the sample length. However, it is inconvenience in this paper as the sample data length is substantial. A parametric study has been performed to determine the best modal order number to be used in the paper.

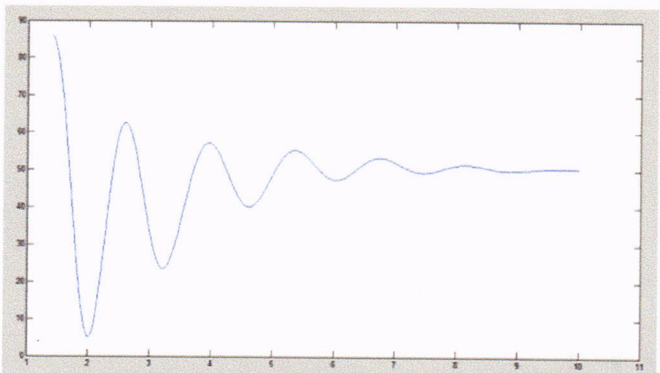

Fig. 2. The example of a power system signal of machine's rotor angle.

The signal in Fig. 2 denoted as y(t) was tested in Prony analysis, using a variety of modal order number, starting from 12 to 150. The mean squared error of the Prony's approximation signal ($y_k(t)$) and the original signal ($y(t)$) was calculated using equation (2) for each of the modal order number set and shown in Table 1.

$$\text{Mean Squared Error} = \sum \frac{(y(t) - y_k(t))^2}{N} \qquad (2)$$

where:
$y(t) = original\ signal;$
$y_k(t) = Prony's\ approximation\ signal;$
$N = sample\ size$

TABLE I
MODAL ORDER NUMBER AND ITS MEAN SQUARED ERROR CALCULATION TO THE ORIGINAL SIGNAL

Modal order number	**Mean squared error (mse)**
12	59.3
50	27.9
100	22.2
120	13.0
130	15.1
140	13.6
150	2090.6

The smaller mean squared error value indicated that the signal is closer to the original signal. Based on Table 1, modal order number of 120 has the lowest value of mean squared error. Fig 3 and Fig 4 shows the comparison of Prony sub-approximation signal ($y_k(t)$) with the measured signal ($y(t)$) between modal order 120 and 150. The figures showed that a high modal order value does not necessarily has the best fit to the measured signal, and the mean squared error value for a high modal order number is not necessarily decreased. Therefore, the modal order number used in this paper is determined based on the lowest calculated mean squared error value.

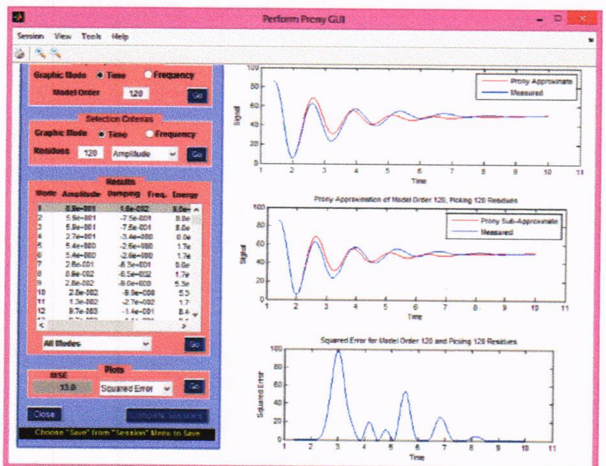

Fig. 3. Prony approximation signal $y_k(t)$ (red) versus the original signal $y(t)$ (blue) for modal order number 120, with the lowest mean squared error value of 13.0.

Fig. 4. Prony approximation signal $y_k(t)$ (red) versus the original signal $y(t)$ (blue) for modal order number 150, with the highest mean squared error value of 2090.6.

Based on Fig. 4, if a modal order number used is 150, Prony analysis will produced 150 different sets of signals. In this paper, the parameter estimation for the best fitting signal is based on research in [6], eliminating distorted components by choosing the biggest result of division between the estimated amplitudes with damping factors. A signal as in Fig 5 was developed using a simple Euler equation of $y = a\, e^{\sigma t} \cos(\omega t)$, whereby all the elements in the equation is predetermined as stated in the Fig. 5. The modal order number used for this test is 12. This test was performed to prove that the biggest result of division between amplitude and damping factors will have the same or closest fit to the original signal. Result obtained in Table 2 shows that the test was a success, and the method of signal selection was adopted in this paper.

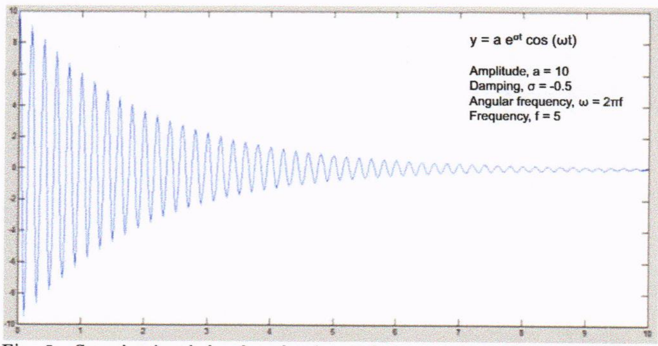

Fig. 5. Sample signal developed using Euler's equation with the amplitude value of 10, damping factor value of -0.5 and frequency value of 5.

TABLE 2
HIGHEST DIVISION OF AMPLITUDE AND DAMPING FOR MODAL ORDER 12 HAS THE EXACT AMPLITUDE, DAMPING AND FREQUENCY VALUE OF TESTED SIGNAL

No.	Amplitude	Damping	Frequency	Amplitude/Damping
1	69.00	-940.00	0.00	0
2	69.00	-940.00	0.00	0
3	10.00	-0.50	5.00	2
4	10.00	-0.50	5.00	2
5	0.00	-0.50	15.00	1E-14
6	0.00	-0.50	15.00	1E-14
7	0.00	-0.50	10.00	1.3E-14
8	0.00	-0.50	10.00	1.3E-14
9	0.00	-0.50	0.00	0
10	0.00	-0.50	25.00	6.4E-16
11	0.00	-0.50	20.00	7.5E-16
12	0.00	-0.50	20.00	7.5E-16

III. POWER SYSTEM SIGNAL'S STABILITY

Power system stability can be classified into three major elements; rotor angle stability, frequency stability and voltage stability [7]. Rotor angle stability depends on the ability of a mechanical torque of a synchronous machine in the system to maintain steadiness with output electromagnetic torque of other generators. Any occurrence of disturbance would sway the rotor angle signal to oscillate. However, the signal must return back to its original state within specified time in order for it to be stable [7]. Signal of rotor angle are taken at a machine's bus. Voltage stability depends on the ability to maintain the equilibrium between reactive power of load demand and load supply from the power system [7]. Instability may occurs in the form of progressive fall or rise of voltages at a bus [7], outside the specified limit of a voltage planning criteria. Frequency stability refers to the ability of a power system to maintain a steady frequency of 50Hz following a severe system upset resulting from a significant imbalance between generation and load. Frequency is measured at a bus and should be equilibrium with other bus located nearby.

The signals of power system are produced in PSSE output file upon performing any dynamic stability analysis. The steps on how to perform PSSE dynamic stability analysis will not be discussed in this paper. The example output file will displayed an output signals as shown in Fig. 6.

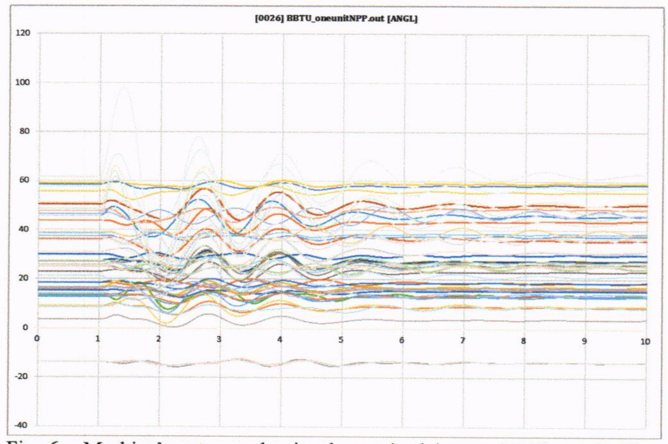

Fig. 6. Machine's rotor angle signal contained in one PSSE output files, depending on the number of channel set by the user or the number of machine contained in a power system network.

Based on Fig.6, it is difficult to determine the stability in each of the signal by using visual interpretation and also tough to calculate each signal's damping ratio. Therefore, an integration program between multiple software of Power System Simulator for engineer (PSSE), Python programming language, Microsoft Excel and MATLAB was created. Once the signal has been produced, Python programming will extract the desired data from PSSE output file, into the Microsoft Excel spreadsheet. Microsoft Excel is widely used as data analysis and data reporting, therefore it is easier for a user to interact. Moreover, the Visual Basic for Application (VBA) embedded in Microsoft Excel can interact with PSSE and MATLAB deprived of having the user to manually open the said program. Data extracted will then be sent to MATLAB to calculate damping ratio using Prony analysis.

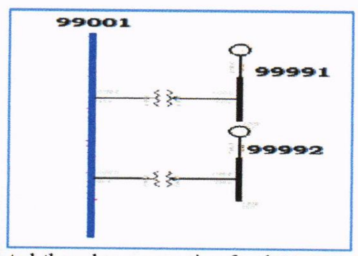

Fig. 7. The targeted three bus connection for data extracting of machine's rotor angle (bus 99991 and bus 99992), and bus 99001 for extracting bus voltage and bus frequency.

As an example, a large power system network comprises of 22,900MW generation with 22,500MW load. A small area of 2,000MW generation connection as shown in Fig. 7 is selected in order to model the stability in the system. This area contains two generators, each produce 1000MW generation. In this network, both voltage and frequency signal were measured at bus 99001, while machine's rotor angle is measured on two generator bus; 99991 and 99992. Losing single generator unit will still produce as stable signal, shown in Fig. 8, while losing both of the generators will produce an unstable signals. Both Fig. 8 and Fig. 9 shows the signal of rotor angle, bus voltage and bus frequency.

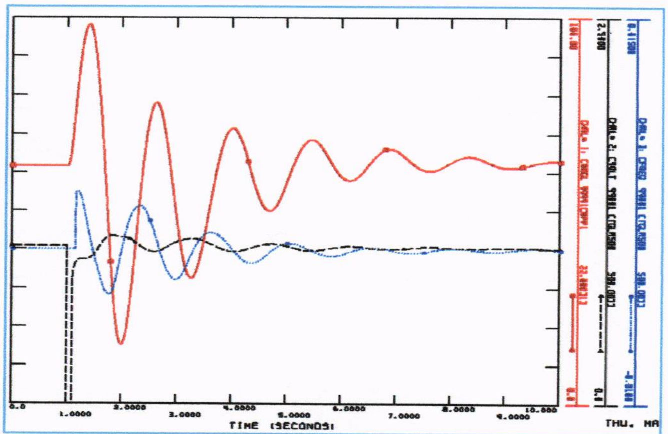

Fig. 8. The signal of rotor angle (red), bus voltage (black) and bus frequency (blue) when losing one of the generator (signals are stable).

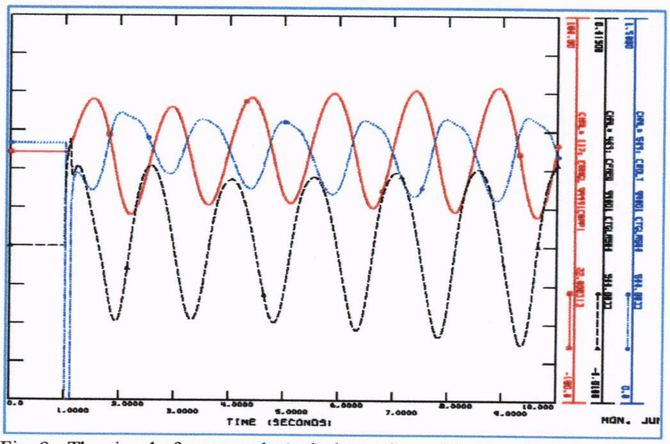

Fig. 9. The signal of rotor angle (red), bus voltage (black) and bus frequency (blue) when losing both of the generators (signals are instable).

Based on the integration program created, signals channel number or bus number has to be pre-selected by the user and listed in the Microsoft Excel spreadsheet. Then, Python programming language will execute its function as a data extractor, extracting total time (t) and output data ($y(t)$) based on its time step (t_2-t_1). Data extracted based on the elements selected between bus voltage (VOLT), bus frequency (FREQ), rotor angle (ANGL) or combination of all three. These data then being tabulated in Microsoft Excel spreadsheet. The critical Python library needed to be imported for this purpose is *dyntools*. Fig. 10 shows the flowchart of Python programming codes used in this paper.

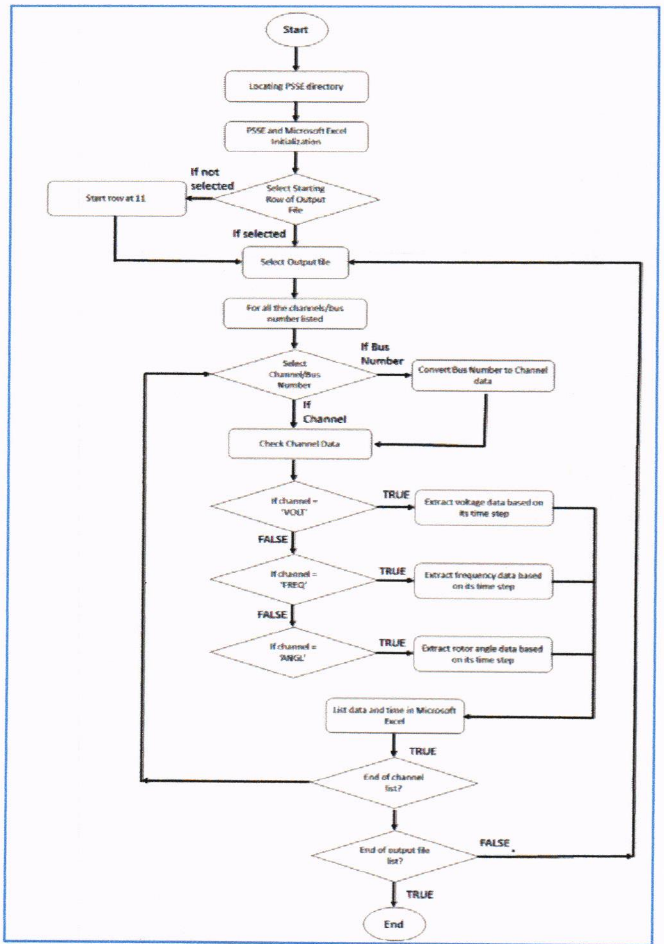

Fig. 10. Flowchart of extracting data from PSSE output file to Microsoft Excel using Python programming language, depending on three selected elements of machine's rotor angle (ANGL), bus voltage (VOLT) and bus frequency (FREQ).

In Microsoft Excel spreadsheet, there are seven steps needed to be followed in order to carefully read, extract and analyze each signal in order to obtain its damping ratio. The spreadsheet is divided into three major part consists of:

- user criteria selection for user input,
- interaction of other programs to list PSSE output files, extract data and transfer to MATLAB, and
- damping ratio result area after performing Prony analysis in MATLAB.

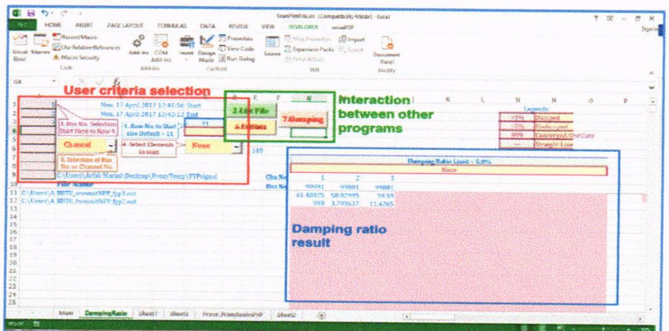

Fig. 11. Three major parts in Microsoft Excel spreadsheet consist of user criteria selection, interaction with other programs and damping ratio result display area.

The flowchart of the steps in Microsoft Excel is shown in Fig. 12. These seven steps comprises of listing all PSSE output file desired, entering element data, extracting data and performing Prony analysis in MATLAB to obtain each signal's damping ratio.

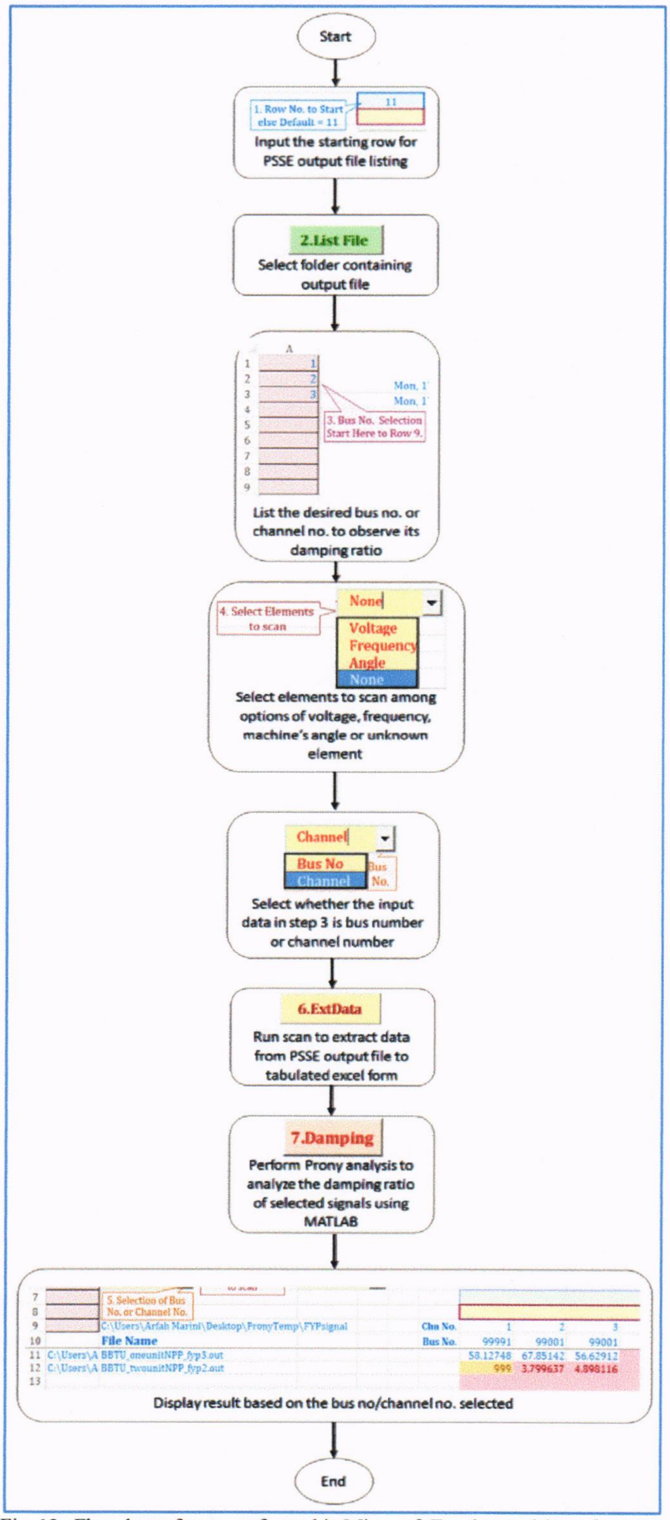

Fig. 12. Flowchart of steps performed in Microsoft Excel spreadsheet, for user to select the desired elements to be extracted, along with the bus number or channel number of the elements needed to find its damping ratio, in a multiple PSSE output file listed.

In MATLAB, the Prony analysis used for this paper is the Pronytool as developed by [5], whereby it calculates the damping components (σ), amplitude (A), frequency (f) and phase (ϕ) based on the number of modal order input. Although Prony analysis could also be performed in PSSE, the Prony output in MATLAB are more accurate. The MATLAB flowchart steps is shown in Fig. 13.

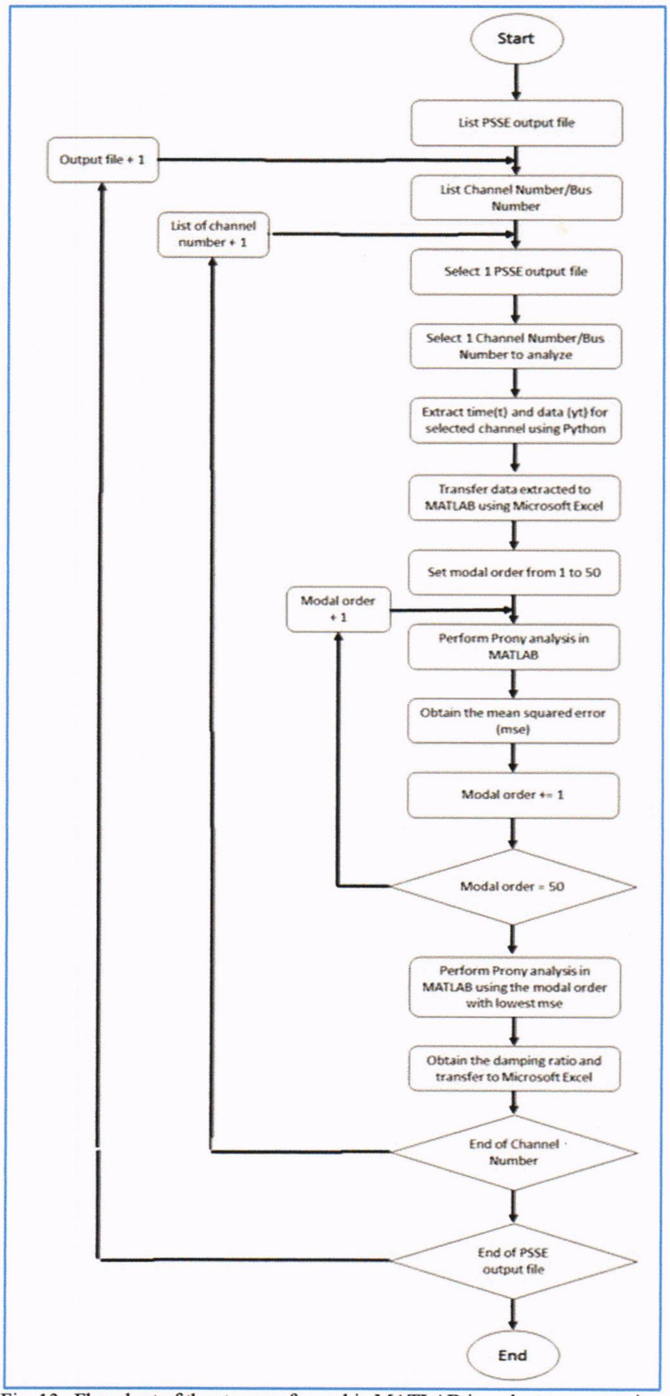

Fig. 13. Flowchart of the steps performed in MATLAB in order to compute its modal order number, and select based on the lowest mean squared error value. Then perform Prony analysis based on the modal order number selected, to calculate each signal's damping ratio, before transfer the result to Microsoft Excel spreadsheet.

IV. Results

Based on the signals of two PSSE output files shown in Fig. 8 and Fig. 9, the results of damping components (σ), amplitude (A), and frequency (f) is obtained through the integration program developed using PSSE, Microsoft Excel and MATLAB. The signal is individually calculated through the loop created in the program. Table 3 shows the result obtained for all of the signals.

TABLE 3
THE RESULT OF AMPLITUDE, DAMPING COEFFICIENT, AND FREQUENCY BASED ON THE MODAL ORDER OF THE LOWEST MEAN SQUARED ERROR VALUE

Case	Element	Modal Order	Amplitude	Damping Coefficient	Frequency
Losing one generator	Rotor angle	33	52.7636	-0.5700	0.7814
	Voltage	14	0.0445	-0.7342	0.7949
	Frequency	45	0.0042	-0.5939	0.8003
Losing both generators	Rotor angle	Signal is not damped			
	Voltage	2	0.1179	-0.0252	0.6624
	Frequency	11	0.0052	-0.0336	0.6850

The signal of rotor angle when losing both of the generators shows an exponential growth to the oscillation, as displayed in Fig. 14. The first maximum value is located at the end of the simulation time, making the signal not having a decay oscillation. Therefore, the signal is not damped, and the damping ratio could not be calculated in Prony analysis. For this case, the signal is denoted as "999".

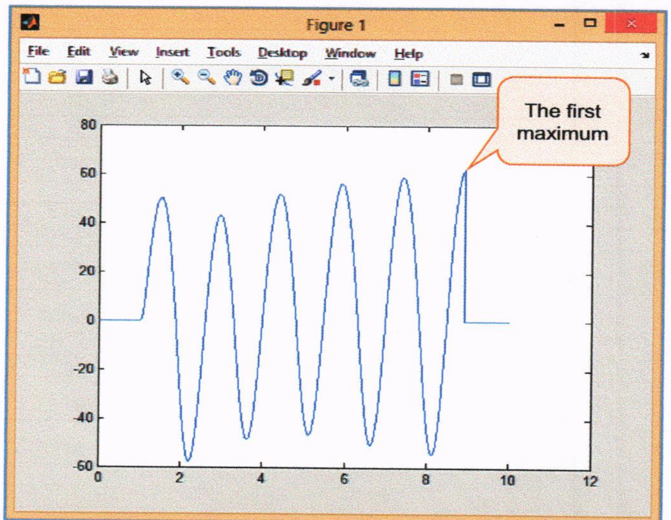

Fig. 14. Signals of rotor angle in the case of losing both generator units, whereby the signals shows an exponential growth oscillation indicating that the signal is not damped.

For other signals measured in Prony analysis, the obtained damping coefficient and frequency are used to calculate damping ratio percentage based on the equation (1) as specified in TSRS standards. The damping ratio and signal stability is shown in Table 4.

TABLE 4
UNITS FOR MAGNETIC PROPERTIES

PSSE Output file	Element	Damping Ratio (%)	Signal Stability
Case 1	Rotor Angle	58.93	Stable
	Voltage	67.85	Stable
	Frequency	59.59	Stable
Case 2	Rotor Angle	999	Oscillate
	Voltage	3.80	Unstable
	Frequency	4.89	Unstable

The final result will be displayed as a final output at Microsoft Excel spreadsheet as shown in Fig. 15. The reason of presenting the damping ratio result in Microsoft Excel instead of reading it at MATLAB program is to avoid the hassle for user to view or open another program. In this case, all the PSSE output file listed, element chosen and result displayed would be on a single platform.

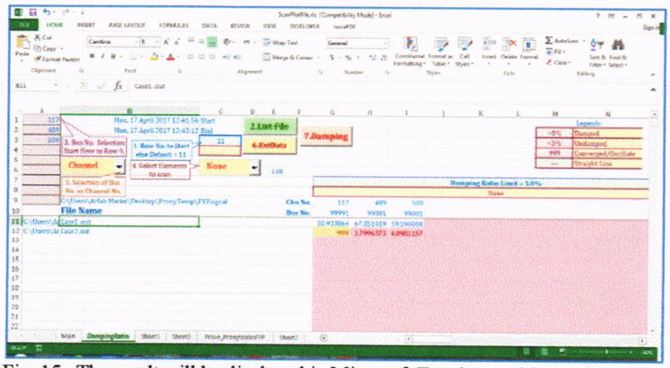

Fig. 15. The result will be displayed in Microsoft Excel spreadsheet, alongside with the PSSE output file listed and elements chosen by the user.

V. Conclusion

As a conclusion, this paper has proved that Prony analysis technique can be used in power system stability analysis, for all three stability elements of machine's rotor angle, bus voltage and bus frequency. This method is used in order to obtain the exact damping ratio value throughout the simulation time to meet the 5% criteria set by Malaysian grid owner planning standards called Transmission System Reliability Standards. Although Prony analysis generate several approximation signal based on the modal order number, the best approximation can be determined using the highest division value between amplitude and damping coefficient produced. Since the modal order number could not be pre-determined by the user, and each of the signal analyzed may have a different modal order number as its closest fit, a method of computing the lowest mean squared error between each of the model order number is considered the best fast detection method to be used.

The integration between multiple software programs of Power System Simulator for Engineer (PSSE), Microsoft Excel, Python programming language and MATLAB simulation program is considered as the best option to obtain the best estimation of damping ratio. In addition, the purpose of having Microsoft Excel Spreadsheet as the base platform to perform the analysis is to ease the user, as the Microsoft Excel is a program that most of users familiarize with. Together with multiple options provided in Microsoft Excel spreadsheet, the user can easily list the desired elements or modify it at a single platform. Microsoft Excel was also chosen as base platform because of its flexibility to interact with both PSSE and MATLAB, using VBA. Plus, multiple PSSE output file can be listed and analyzed at once. Therefore it can save a lot of users' time. As an advantage to the power system network planning industry, having a fast calculation of damping ratio can allow network planners to eliminate the stable area, and focus on the problematic ones to have ample time in mitigation and rectification work to the system.

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