ERCIM "ALAIN BENSOUSSAN" FELLOWSHIP PROGRAMME

Scientific Report

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I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

During one year ERCIM fellowship, I have concentrated on the general subject of phasor estimation in a power system. Phasor estimation is crucial for monitoring and control of the smart power systems.

Today's power systems are becoming increasingly complex due to new components and intermittent resources. At the same time, there is a need for enhanced utilization of the existing infrastructure. Reduced margins require more precise knowledge about the system state. The considerable penetration of renewable energy resources and inverter-fed generations changes the dynamics of the system. Use of Synchronized Measurement Technology represented by Phasor Measurement Units (PMUs) appears to be an approach that will contribute to cover the requirements of monitoring and smart control. Different identification algorithms can be applied to signals measured by Phasor Measurement Unit (PMU) to estimate states of systems.

During this fellowship, I have worked more on a promising algorithm named Prony where estimates are calculated adaptively. I have managed to improve its performance under different conditions by using new concepts and make it more efficient for real time applications.

I started my research on the recursive multi-channel Prony to make this algorithm suitable for real time applications. Afterward, I focused on the tuning parameter of recursive Prony and proposed a modified recursive Prony to reach a compromise under both steady state and dynamic conditions. Next, the Prony algorithm is armed with the

Empirical Mode Decomposition (EMD), which detects the number of oscillating modes in a pure signal and so makes the Prony more efficient under harmonic and noise conditions. Then, I worked on a general concept of adaptive phasor estimation and it has been shown that it is more efficient concept than the static and dynamic phasor estimation algorithms. Finally, I am working on the phasor estimation under fault conditions based on the level of nonlinearity and utilization of online EMD for estimation of the phasor. brief explanations for all the mentioned subjects are as follow:

1. **Recursive Multi-channel Prony for Real-Time Phasor Estimation:** The classical signal processing method named Prony has been used for estimating the parameters of measured signals such as frequency, damping factor and phasor. To reduce the impact of noise on the parameters estimated by Prony, multi-channel Prony has been previously explored and presented in the literature. The basic approach for multi-channel Prony is a generalized solution, in which new rows are added to matrices for every channel. Since the generalized multi-channel Prony is time-consuming, a new method based on a recursive solution is proposed in this paper to make it suitable for real-time application. Several channels of one Phasor Measurement Unit (PMU) are used to estimate the phasor of current/voltage in a recursive pattern, thus speeding up the algorithm by utilizing the previous estimates for the in-going measurements. The proposed method is applied to real data: (a measured current from a real power system, processed offline in MATLAB, b) measured voltage from National Instrument devices, processed online in LABVIEW. Both synthesized and real data demonstrate the efficient performance of the proposed method in the phasor estimation application. The results of this part of my research is presented in [1] and [2].

2. **Phasor Estimation based on Modified Recursive Prony:** According to the IEEE Standard for synchrophasors (IEEE C37.118.1), the phasor estimation algorithms must be examined in steady state and under dynamic conditions. In this part of my work, the performance of the recursive Prony under both conditions is examined. Accordingly, a new parameter named, ''*Forgetting Factor* (λ)", is used in the phasor estimation process giving exponentially less weight to the older error samples. The impact of λ on the performance of the recursive Prony is analysed in steady state and under dynamic conditions. The results indicate that higher values of λ provides more accurate estimation at the expense of a longer delay under dynamic conditions. In contrast, lower values of λ provides faster response at the expense of accuracy of estimation. Based on this analysis, a time varying λ (TVλ) is implemented as a trade-off between the performance requirements under steady state and dynamic conditions. According to the obtained results from the modified recursive Prony, this method can satisfy both steady state and dynamic objective function performance requirements simultaneously. The results of this part of my research is presented in [3].

3. **EMD-Prony for Phasor Estimation in Harmonic and Noisy Condition:** For fundamental phasor estimation, the Prony algorithm with the order of one is suitable but its performance in terms of accuracy is diminished when non-fundamental components interfere in the measured signal. These components can be eliminated

from fundamental phasor estimates by increasing the Prony's model order. In order to specify adaptively the order of the Prony algorithm, the Empirical Mode Decomposition (EMD) method is proposed in this paper to be combined with the Prony algorithm as EMD-Prony. The EMD decomposes a signal into finite Intrinsic Mode Functions (IMF) based on the number of modes in the measured signal. The number of IMFs is utilized by Prony to extend its model to higher order and so purifies the fundamental phasor estimates. In addition, EMD is also used as a pre-processor to filter the noise from the input signal of Prony. Finally, the proposed method can estimate phasor accurately in noisy and harmonic conditions. The results of this part of my research is presented in [4] and [5].

4. **Efficient Phasor Estimation under Steady State and Dynamic Conditions:** Classical phasor estimation proposed many years ago, considers the phasor to be time independent which means constant amplitude and phase. However, the dynamic phasor concept introduced recently, improves the accuracy of the phasor estimation under a non-stationary signal as is typically the case of low frequency oscillations (LFO). However, more accurate estimates lead to higher computation time. To achieve both low computation time and more accurate estimates, an adaptive phasor estimation concept based on both static and dynamic phasors is proposed. A new method based on the *Adaptive Prony* algorithm is presented, in which the *Static Prony* is employed under steady state conditions and the *Dynamic Prony* under dynamic conditions. To switch between these two algorithms, a Cumulative Summation of the Phasor Estimation Error (CSPEE) is used. Simulation results show the applicability of the proposed method to achieve the most accurate estimates at the lowest computation time. The results of this part of my research is presented in [6].

5. **Online Estimation by Empirical Mode Decomposition based on Degree of Non-linearity:** Empirical Mode decomposition (EMD) is a nonlinear decomposition algorithm that breaks an input signal into different frequency modes. Unlike to other methods as wavelet, Fourier or Prony, it uses data driven model for input signal and so provides adaptive model for parameter estimation procedure. In this algorithm, spline interpolation is used for making upper and lower envelopes and use sifting process to extracts different Intrinsic Mode Functions (IMFs). Although it shows the best performance in nonlinear conditions, applying EMD in linear condition is not reasonable. In this part of my work, it is shown that parameter estimation of linear input signal should be done by linear methods and nonlinear signal is done by EMD. Therefore, parameter estimation should be done based on degree of non-linearity of a signal that Auto-regressive model is used here. Auto-regressive model provides linear prediction of future sample based on previous samples. Finally, based on degree of non-linearity (DNL), EMD is used when the DNL is larger than a threshold value and classical linear methods are used when DNL is less than threshold. The results of this part of my research is presented in [7].

II – PUBLICATION(S) DURING YOUR FELLOWSHIP

During the fellowship, I have written seven papers. Three of them were presented in the conferences, one of them will be presented in the October and three of them are mostly completed but need some final editing before submission. The papers are listed as follows:

[1] J. Khodaparast, O. B. Fosso, M. Molinas, *Real Time Phasor Estimation based on Recursive Prony with Several Channels of One PMU*, IEEE conference ISGT 2018, Sarajevo, Bosnia and Herzegovina.

[2] J. Khodaparast, O. B. Fosso, M. Molinas, *Recursive Multi-channel Prony for Real-Time Phasor Estimation*, IEEE Transaction on Power System, In process.

[3] J. Khodaparast, O. B. Fosso, M. Molinas, *Phasor Estimation based on Modified Recursive Prony*, IEEE conference CCTA 2018, Copenhagen, Denmark.

[4] J. Khodaparast, O. B. Fosso, M. Molinas, *EMD-Prony for Phasor Estimation in Harmonic and Noisy Condition*, IEEE conference SPEEDAM 2018, Amalfi, Italy.

[5] J. Khodaparast, O. B. Fosso, M. Molinas, *Adaptive Order Prony with Empirical Mode Decomposition*, IEEE Transaction on Power System, In process.

[6] J. Khodaparast, O. B. Fosso, M. Molinas, *Efficient Phasor Estimation under Steady State and Dynamic Conditions*, IEEE conference SEST 2018, Sevilla, Spain.

[7] J. Khodaparast, O. B. Fosso, M. Molinas, *Online Estimation by Empirical Mode Decomposition based on Degree of Non-linearity*, In process.

III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

During the fellowship, I attended in three conferences and I will attend in the fourth conference in October 2018. The conferences are as follows:

1. **IEEE conference SPEEDAM 2018, Amalfi, Italy**, 20-22 June 2018.
2. **IEEE conference CCTA 2018, Copenhagen, Denmark**, 21-24 August 2018.
3. **IEEE conference SEST 2018, Sevilla, Spain**, 10-12 September 2018.
4. **IEEE conference ISGT 2018, Sarajevo, Bosnia and Herzegovina**, 21-25 October 2018.

IV – RESEARCH EXCHANGE PROGRAMME (REP)

Instituto de Engenharia de Sistemas e Computadores (INESC), Portugal.
Prof. João Catalão, Senior Researcher at INESC.
13-20 September, 2018.
I will do my REP at INSEC and I will work with Prof. Catalão and his team, which have great contributions in mathematical analysis of the power system. During this time, I presented about all I have done in my one year Postdoc at NTNU and will discuss about possible collaboration between NTNU and INSEC in the near future.