Hardware-in-the-loop (HIL) Testing of Synchrophasor Based Out-of-Step Protection

J. R.A.K. Yellajosula, S. Paudyal, B. A.Mork, S. Paravastu, and H. Kr. HØidalen

***Abstract*--This paper presents real-time hardware-in-the-loop (HIL) simulation of synchrophasor measurements based out-of-step protection using Zubov's approximation stability boundaries. Out-of-step decision algorithms mathematically mean solving the swing equations after disturbances. Instead of directly solving a system of partial differential equations, we track angle-frequency trajectories derived from the synchrophasor measurements and compare them against the Zubov's boundaries to detect out-of-step conditions. The proposed out-of-step detection algorithm is tested in closed loop using a single-machine infinite bus system (SMIB), where the transient model is developed in OPAL-RT and NI-cRIO is used to model the out-of-step detection algorithm.**

***Keywords*: Real-time simulation, Hardware-in-the-loop, Out-of-step protection, Power system protection, OPAL-RT, NI-cRIO, LabVIEW.**

I. INTRODUCTION

DISTURBANCES such as faults, sudden load change, loss of generators, etc., in electric power systems are common and inevitable. Disturbances cause transients in the power systems and may impact system stability depending on the severity [1].

Protection of the power system is one of the most important and challenging real-time tasks in the networked grid. Transient stability is one of the major concerns for protection schemes, as the decision time to trip is in the seconds. At least five major blackouts have occurred in North American power system from various disturbances since 1960, and out-of-step is one of the major causes [2].

Power system protection has always played a crucial role in securing the network and isolating the faulted zone. This protection is provided by relays, which is defined as *"an electric device that is designed to respond to input conditions in a prescribed manner and, after specified conditions are met, to cause contact operation or similar abrupt change in associated electric control circuits"* [3]. Protective relaying involves reading the input measurements from current and voltage transformers, executing the functional logic and providing decision via a wired trip output [4]. The primary objective of any protection scheme is to detect and isolate the faulted network, such that it should not lead to cascading blackout. Disturbances such as voltage dip, loss of line, under frequency, and loss of field are a few of the major reasons, which if left unattended, would lead to instability and cascaded blackout of the grid [5].With ever-expanding power network grids and recent developments in the field of digital communications and smart grid technologies, there is always scope to revise the existing protection relay functioning logic.

Early detection and faster response of the faults are the prime objectives in the digital protection era. With the advancements in phasor measurement devices [6] and communication advancements in substation automation [7], it is possible to obtain information at higher sample rate. With the availability of phasor measurements, i.e., voltage, current, frequency, and rate of change of frequency (ROCOF), and with additional algorithms to obtain machine angles, novel and computationally effective algorithms for detection and isolation of transient instabilities in the power grid can be designed [8]. In addition to these advancements, there are also real-time simulators which are used for planning and offline performance testing of protection schemes [9]. These simulators would help to model and test the protection logic of large complex power systems and with the availability of communication channels it can be easily mocked to perform the actions of substation automation [10]. Modern protection relays serve multiple functionalities, which calls for offline testing of the protection schemes. With the advancements in real-time simulators (e.g., OPAL-RT and RTDS), it is possible to simulate the fault scenarios in closed-loop and modify the relay settings for improved performance. With all these functionalities, real-time simulators can be used to precisely model and playback an event (fault or blackout) and also examine grid dynamics. This could help the protection engineer to study, analyze and design the settings in an effective manner.

In this paper, real-time simulation of synchrophasor measurements based out-of-step protection is setup and introduced. It is based on OPAL-RT OP5600 simulator [11] and synchrophasor measurements are obtained from software simulation via MATLAB/SIMULINK. An out-of-step algorithm is then modelled and simulated with the help of NI-cRIO [12]. Zubovs approximation boundaries are used to design the out-of-step logic and this boundary method is based on Lyapunov's stability analysis [13]. This paper is an extension to the software simulation carried out in our previous work [18]. In this paper, we used the algorithm derived in [18],

Laboratory development and implementation for this work was partially supported by the Research Council of Norway KPN "ProSmart" project via NTNU, Trondheim, Norway

J. R. A. K. Yellajosula, S. Paudyal, B. A. Mork, and S. Parvastu are with Michigan Technological University, Houghton MI 49931 USA (e-mail of corresponding authors: jyellajo@mtu.edu, sumitp@mtu.edu, bamork@mtu.edu and sparvas@mtu.edu).

H. Kr. Høidalen is with is with the Norwegian University of Science and Technology, N-7491 Trondheim, Norway. (E-mail of corresponding author: hans.hoidalen@ntnu.no).

Paper submitted to the International Conference on Power Systems Transients (IPST2017) in Seoul, Republic of Korea June 26-29, 2017

and implemented and carried out the HIL simulations using a SMIB system to test the closed-loop performance of the algorithm.

The rest of the paper is organized as following. Section II provides the mathematical modeling of the Zubov's approximation boundaries. Section III provides the setup and implementation of the simulations. Section IV examines different cases with stable and unstable swings, which are used to evaluate the performance of the out-of-step detection algorithm. Finally, conclusions are provided in the Section V.

II. Mathematical Modeling

In this section, mathematical modeling for out-of-step protection is presented, which is available in [13], [14] in detail. The core implementation of this mathematical modeling is derived from Lyapunovs second method for nonlinear analysis. Zubov's method provides modification to the Lyapunov's method, which is approximate but is proven to be efficient in numerical analyses [15]. The approximation boundaries represent the solution to the partial differential equations in the stability region. The basic of Zubov's method is provided by the following equation,

$$\sum_{i=1}^{n} \frac{\partial V}{\partial x_i} F_i = -\phi(1-V) \tag{1}$$

Where,

$\emptyset$ is an arbitrary positive-definite function,

V is assumed to be sum of an infinite series of homogenous polynomial [16]. In general, any steady state system can be represented as,

$$\dot{x} = Ax + g(x) \tag{2}$$

Where A is the linear equation and *g(x)* is the summation of higher degree polynomials, which represents the non-linearity in the system. In (1), V represents summation of nonlinear polynomials which can be written as,

$$V = V^N = V_2(x) + V_3(x) + \cdots + V_N(x) \tag{3}$$

Where $V_2(x)$ is quadratic in x and $V_N(x)$, *N = 3, 4…* are homogeneous equation in *N* degree.

By substituting (3) in (1), $V_N(x)$ could be calculated as,

$$\sum_{i=1}^{n} \frac{\partial V_N(x)}{\partial x_i} F_i(x) = -\phi V^{N-2} \tag{4}$$

Where the V^2 is,

$$\sum_{i=1}^{n} \frac{\partial V_2(x)}{\partial x_i} F_i(x) = -\phi \tag{5}$$

A numerical example for this mathematical solution can be found in [13].

Fig. 1, represents the single machine infinite bus (SMIB) system [17], which is used as base to implement the above derived mathematical formulation for approximation boundaries. The swing equation of the SMIB system can be defined as,

$$M\frac{d^2\delta}{dt^2} + D(\delta)\frac{d\delta}{dt} + P_m \sin\delta + P_s \sin 2\delta = P \tag{6}$$

Where M is machine inertia constant, δ is machine's power angle, $D(\delta)$ is the damping factor, Pm is the mechanical input power, and P_S is the synchronizing power.

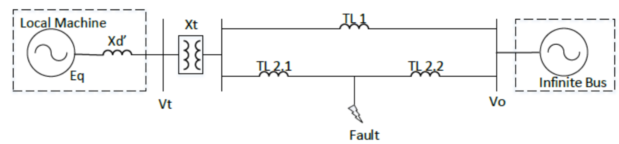

Fig. 1 Single Machine Infinite Bus System.

At stable equilibrium, power angle is constant and their derivatives corresponds to zero

$$\delta = \delta_o \tag{7a}$$

$$\dot{\delta} = \ddot{\delta} = 0 \tag{7b}$$

Where, δ_0 is the initial power angle. The system of equations are transferred to a new reference by assuming $\delta = \delta_0 + \delta'$ Equation (6) can be rewritten as,

$$\frac{d^2\delta'}{d\tau^2} + D'(\delta')\frac{d\delta'}{d\tau} + R(\delta') = 0 \tag{8}$$

Where,

$$D(\delta) = \underbrace{\frac{V_o^2\,(x'_d - x''_d)\,\tau''_{do}}{(x'_d + x)^2}}_{a} \sin\delta^2 + \underbrace{\frac{V_o^2 (x'_q - x''_q)\,\tau''_{qo}}{(x'_q + x)^2}}_{b} \cos\delta^2 \tag{9}$$

$$D'(\delta') = D_o + \sum_{n=1}^{\infty}\left\{\frac{2^n}{n!}\left(\frac{a-b}{2}\right)\cos\left(2\delta_o + \frac{n\pi}{2}\right)\right\}\delta'^n \tag{10}$$

Where D_0 is calculated as,

$$D_o = \frac{a+b}{2} + \frac{a-b}{2}\cos(2\,\delta_o) \tag{11}$$

$$R(\delta') = P' - \sin(\delta_o + \delta') - P'_s \sin(2\delta_o + 2\delta'). \tag{12}$$

Equations (10) and (11) can be expanded as higher order polynomials as,

$$D(\delta') = D_o + D_1\,\delta' + D_2\,\delta'^2 + D_3\,\delta'^3 + \ldots \tag{13}$$

$$R(\delta') = R_1\,\delta' + R_2\,\delta'^2 + R_3\,\delta'^3 + \ldots \tag{14}$$

State variables of the swing equations are defined as $\dot{\delta}' = \omega'$, where ω' represents speed of the governor. The system dynamics can be represented as,

$$\dot{\delta}' = \omega' \tag{15}$$

$$\dot{\omega}' = -D(\delta')\,\omega' - R(\delta') \tag{16}$$

Equations (15) and (16) can be expressed as function of partial derivatives through which Zubovs method could be applied for obtaining the approximation boundaries,

$$\left\{\nabla U(\delta',\omega')\right\}^T f_i(\delta',\omega') = -\phi(\delta',\omega')\left\{1 - U(\delta',\omega')\right\} \tag{17}$$

Where,

$$U = U^N = \sum_{i=2}^{N} v_i(\delta', \omega') = \sum_{i=2}^{N} \sum_{k=2}^{i} d_{ik} \delta'^{i-k} \omega'^{k} \qquad (18)$$

Where $v_i(\delta', \omega')$ is homogeneous polynomial of degree *i*. By expanding the polynomial *U*, stability boundaries can be obtained.

For $N = 2$,

$$d_{20}\,\delta'^{2} + d_{21}\,\delta'\,\omega' + d_{22}\,\omega'^{2} = C_2 \qquad (19)$$

For $N = 3$,

$$d_{30}\,\delta'^{3} + d_{31}\,\delta'^{2}\,\omega' + d_{32}\,\delta'\,\omega'^{2} + d_{33}\,\omega'^{3} = C_3 \qquad (20)$$

In above equations, $\emptyset$ is an arbitrary positive-definite function, which is defined as $\emptyset(\delta', \omega') = \alpha\delta'^2 + \beta\omega'^2$, where $\alpha + \beta = 1$. $U(\delta', \omega') = C$ represents the zubov's stability boundaries. The constants C, i.e., $C_2, C_3, ..etc,$ are determined from system pre-fault δ_0 and ω_0 values.

III. Hardware Setup

The schematic of hardware implementation setup is shown in Fig. 2. SMIB model is developed in OPAL-RT OP5600 simulator, while the out-of-step detection algorithm is developed in the NI-cRIO device [12]. In the proposed work, SMIB model is developed using MATLAB/SIMULINK and this model is exported to OPAL-RT with real-time model elements for synchronous generator, transmission lines and real-time scope for monitoring and storing the data points.

Fig. 2 Overview of hardware connections

Fig. 3 shows the general flow of the data and procedures for the HIL testing. Implementation of the out-of-step algorithm is done in NI-cRIO using LabVIEW [12]. Five Zubov's boundaries, as shown in Fig. 4, are created in the $\delta - \omega$ plane using (18) for N = 2, 4, 6, 8 and 10. These boundaries are represented as H1, H2, H3, H4, and H5 in Fig. 4, which are stable boundaries designed to detect the stable swings of different magnitudes. By having multiple boundaries it would help the power system operator to categorize the remedial actions for the stable swings. In addition, a new boundary is also created which will be used to detect the out-of-step condition, this boundary provide the trip signal to the system, and this is shown in fig.5. The boundary settings are calculated using machine pre-fault conditions. For out-of-step detection, as the $\delta - \omega$ trajectory passes through the outermost boundary, which will imitate the trip signal to breakers. During system stable operation or during power swings, the decision is made by a sequence of time delays (Delay 1-Delay 5) corresponding to each boundary. The delay settings are provided in detail in [13]. For stable swing cases, the trajectory will always settle at a new steady state condition. Distinguishing between stable boundaries and unstable out-of-step boundaries would help power system operators to differentiate the stable swings from out-of-step and also could be used as decision making in emergency control.

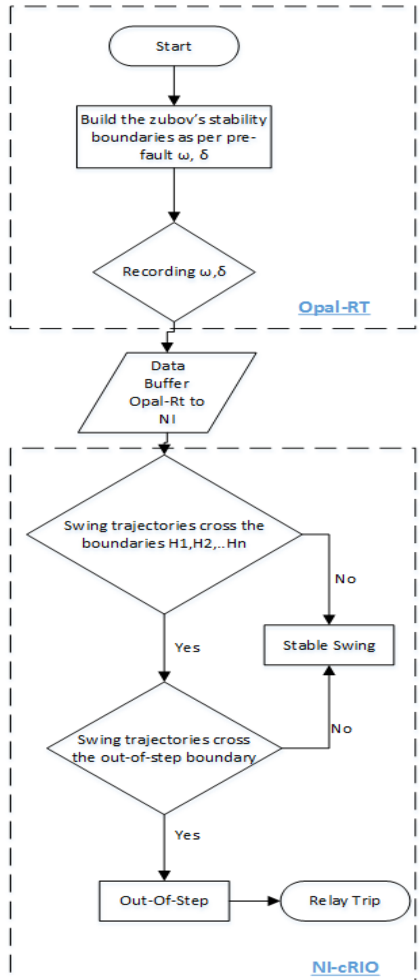

Fig. 3 Flowchart of the HIL testing Process.

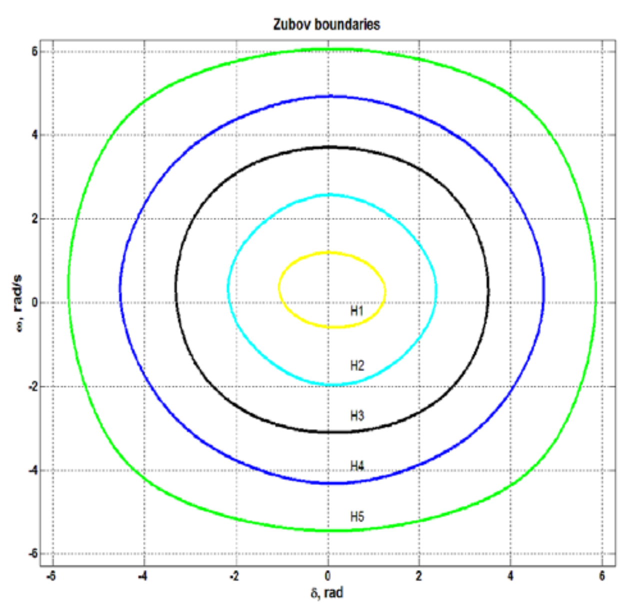

Fig. 4 Zubov's stability boundaries

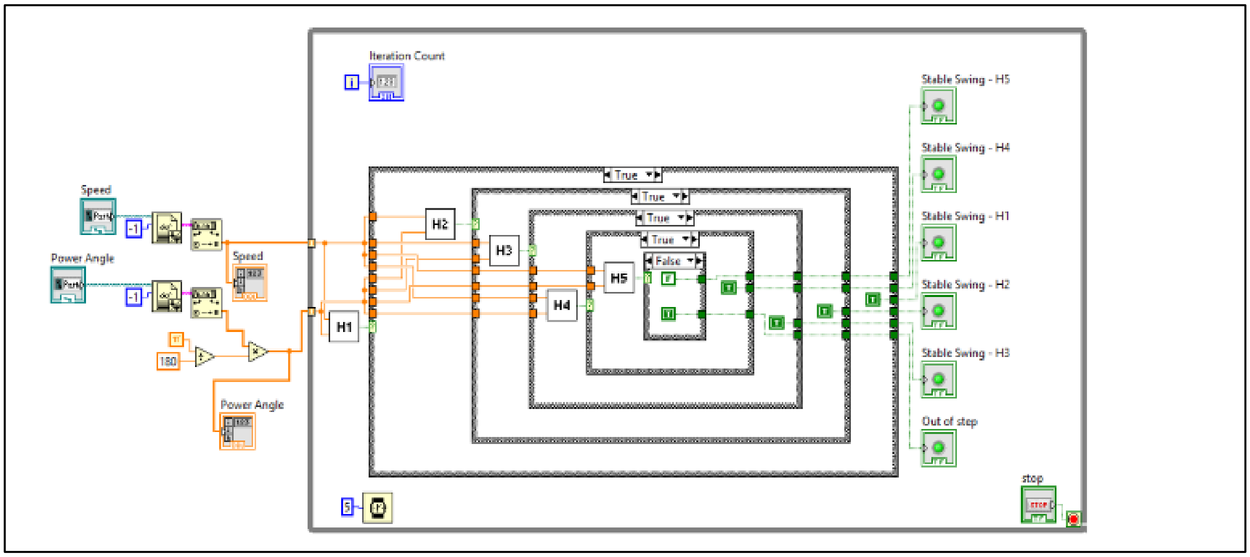

Fig. 5 Zubov's boundaries implementation in LabVIEW

IV. Case Studies

The SMIB system [17] shown in Fig. 1, is used for the case studies. A few cases are presented here to demonstrate the real-time performance of the proposed method in detecting stable swing and out-of-step conditions. The pre-fault machine angle and speed are set at $\delta = 21.4^o$ and $\omega = 1\ pu$. A three-phase to ground fault was applied at the middle of line-2 as represented in Fig. 1. For the stable swing case, the fault duration is set to 0.14 s, respectively, and for the case of out-of-step condition the fault duration is set to 0.38 s.

Fig. 6 and 7 represent the stable swing characteristics and decision made by NI-cRIO for stable swing. For this case, the $\delta - \omega$ trajectory passes through boundary H1 only.

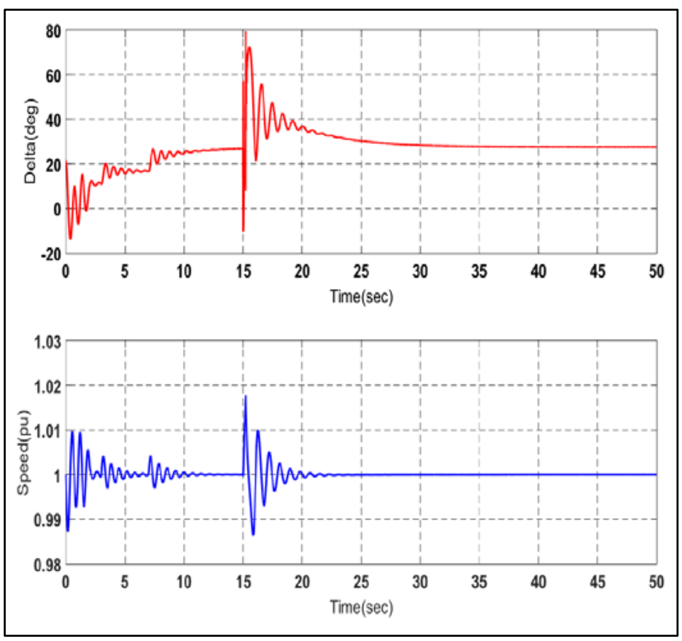

Fig. 6 Stable swing case

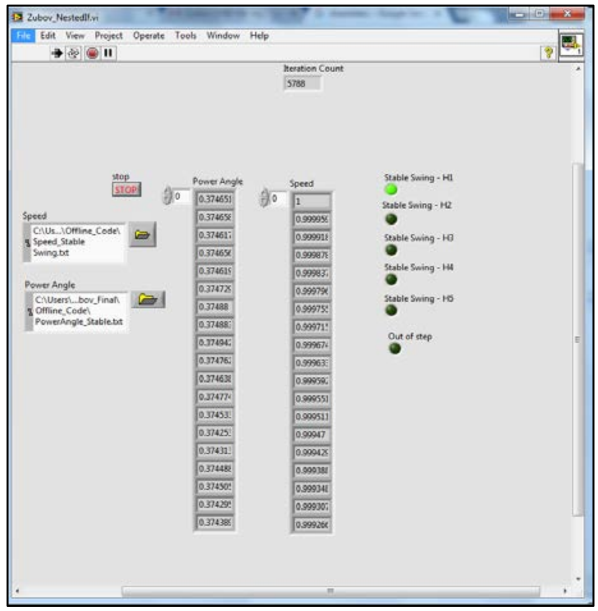

Fig. 7 NI-cRIO response for stable swing

Fig. 8 and 10 represent the unstable swing characteristics and decision made by NI-cRIO for unstable swing. For this case, the $\delta - \omega$ trajectory passes through boundary H5 and provides out-of-step trip signal.

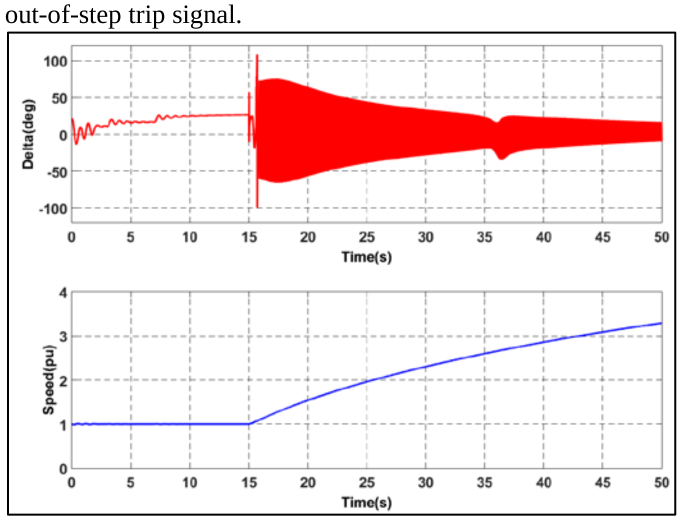

Fig. 8 Unstable swing case

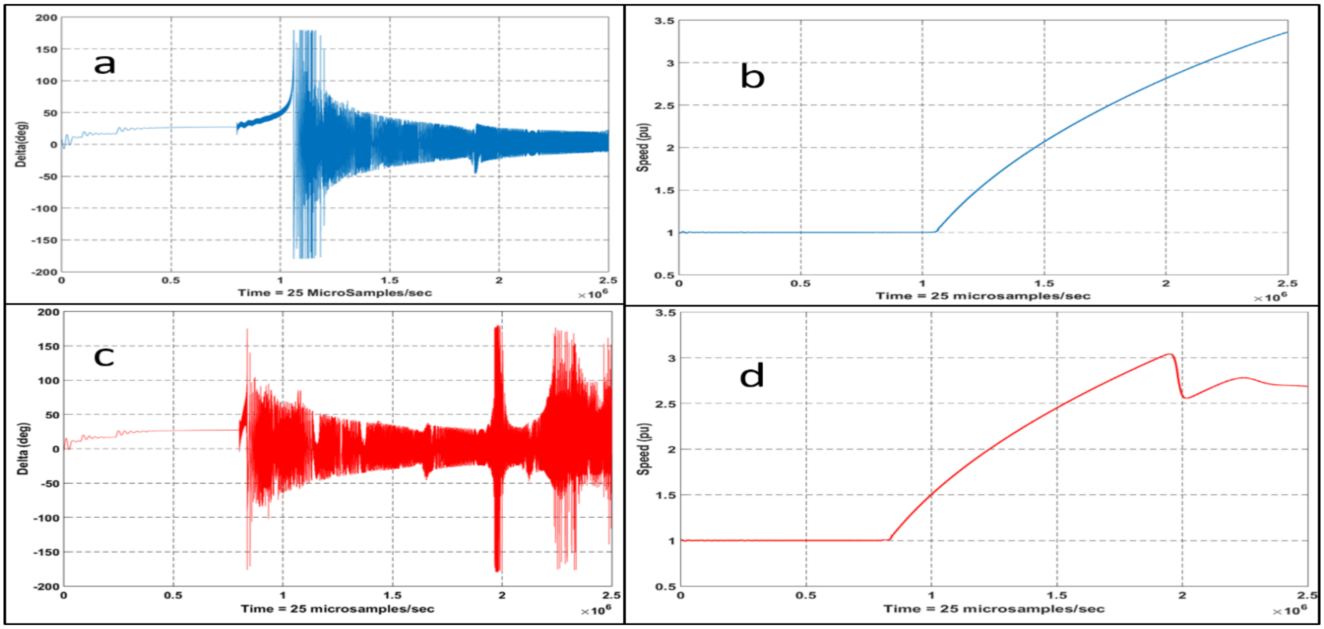

Fig. 9 a) Delta for 1LG fault b) Speed for 1LG fault c) Delta for LL fault d) Speed for LL fault

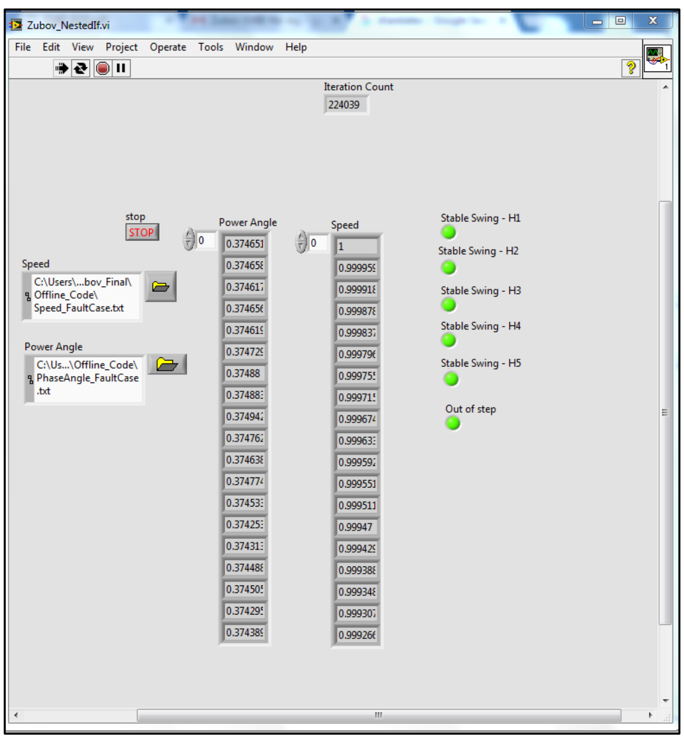

Fig. 10 NI-cRIO response for unstable swing

Both the cases provides an overview of the algorithm and its ability to differentiate stable and unstable swings. In addition to this, couple more cases were simulated to check the effectiveness of the algorithm for unbalanced faults and LabVIEW was used to obtain trip times for each case. Fig 9 provides the overview of speed and delta during 2 unbalanced faults (LL and 1LG), these faults were not tripped out of the system, this is done to calculate the trip times for maximum allowable stable swing (i.e.. before crossing H5 boundary) time and also trip time for the out-of-step condition, these were tabulated in table-I, these were derived from LabVIEW.

In overview the proposed algorithm does identify both unstable and stable swings during balanced and unbalanced faults, which would provide opportunity to execute the logic in real-time on multi-machine network and NI-cRIO could act as a relay.

Table 1 Trip decision for different faults

Fault Type	Trip time from NI-cRIO (sec)	Trip time from offline simulation (sec)
3LG fault (0.38sec)	0.26	0.34
1LG fault (0.38sec)	0.32	No offline were simulations performed
LL fault (0.38sec)	0.28	

Real-time simulations provide data with higher sampling rate, which could be used to provide faster detection and trip of fault conditions. One of the reasons behind performing real-time simulations is to visualize the data at higher resolution, which could help the detection algorithms to trip fast and this is what achieved in this work.

V. Conclusion and Future Scope

In this paper, HIL simulations of the proposed power system out-of-step detection method based on Zubov's approximation stability boundaries are performed. The objective of this work is to develop a real-time power system HIL testing platform using OPAL-RT's OP5600 simulator and NI-cRIO at the laboratory level to test the out-of-step protection algorithm. Test cases were developed and validated for stable and unstable swings. As a future scope, a multi-machine power system with Phasor Measurement Units (PMU) hardware in loop and advanced communications (using IEEE c37.118.2 [19]) are planned for this work.

VI. References

[1] P. Kundur, *Power System Stability and Control.* New York: McGraw-Hill, 1994.

[2] "The Smart Grid: An Introduction", U.S. Department Of Energy Report. [Online]. Available: http://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE SGBook Single Pages%281%29.pdf

[3] *IEEE Standard for Relays and Relay Systems Associated with Electric Power Apparatus* in ANSI/IEEE Std C37.90-1989, vol., no., pp.01-, 1989 doi: 10.1109/IEEESTD.1989.94810.

[4] J.L.Blackburn, and T.J. Domin, *Protective relaying: principles and applications.* CRC press, 2015.

[5] R. D. La and A. G. Phadke,"Catastrophic Failures in Power Systems: Causes, Analyses, and Countermeasures," Proceedings of the IEEE, Vol.93 (5), pp. 956-964, May, 2005.

[6] A. G. Phadke, *Synchronized phasor measurements and their applications*. Springer Science Business Media, 2008.

[7] J. D. McDonald, "Substation automation. IED integration and availability of information," in *IEEE Power and Energy Magazine, vol. 1, no. 2, pp. 22-31, Mar/Apr 2003. doi: 10.1109/MPAE.2003.1192023*

[8] M. Adamiak, B. Kasztenny, & W. Premerlani, "Synchrophasors: definition, measurement, and application" Proceedings of the 59th Annual Georgia Tech Protective Relaying, Atlanta, GA (2005): 27-29.

[9] R. M. Reddi and A. K. Srivastava, "Real time test bed development for power system operation, control and cyber security," North American Power Symposium 2010, Arlington, TX, 2010, pp. 1-6. doi: 10.1109/NAPS.2010.5618985

[10] M. S. Almas, R. Leelaruji and L. Vanfretti, "Over-current relay model implementation for real time simulation & Hardware-in-the-Loop (HIL) validation," IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society, Montreal, QC, 2012,pp. 4789-4796.

[11] OPAL-RT Technologies Inc. [Online]. Available: http://www.opalrt. com/product/artemis

[12] National Instruments Inc. [online]. Available: http://www.ni.com/compactrio/

[13] Y. Wei, "Out-of-step Detection Based on Zubov's Approximation Boundary Method," MSc. Thesis, Michigan Tech. Univ., Dept. of Elect. And Comput. Eng., Houghton, MI, 2014.

[14] M. A. Pai, Power System Stability Analysis by the Direct Method of Lyapunov, New York: North-Holland, 1981.

[15] Y. Yannan and K. Vongsuriya, "Nonlinear Power System Stability Study by Liapunov Function and Zubov's Method," IEEE Trans. Power App. Syst., Vol. PAS-86(12),pp. 1480- 1485, April, 1967.

[16] V. I. Zubov, "Voprosy teorii vtorogo metoda Lyapunova, postroenie obshchego resheniya v oblasti asimptoticheskoi ustoichivosti,(Problems in the theory of the second method of Lyapunov, construction of the general solution in the domain of asymptotic stability)" Prikladnaya Matematika i Mekhanika, Vol. 19, pp. 179-210, 1955.

[17] Y. n. Yu and K. Vongsuriya, "onlinear Power System Stability Study by Liapunov Function and Zubov's Method," IEEE Transactions on Power Apparatus and Systems, vol. PAS-86, no. 12, pp. 1480-1485, Dec. 1967. doi: 10.1109/TPAS.1967.291911

[18] Y. Wei, S. Paudyal and B. A. Mork, "Out-of-step detection using Zubov's approximation stability boundaries," 2015 IEEE Power Energy Society General Meeting, Denver, CO, 2015, pp. 1-5. doi: 10.1109/PESGM.2015.7286595

[19] *IEEE Standard for Synchrophasor Data Transfer for Power Systems*, in IEEE Std C37.118.2-2011 (Revision of IEEE Std C37.118-2005) , vol., no., pp.1-53, Dec. 28 2011 doi: 10.1109/IEEESTD.2011.6111222