Predictive Mitigation of Short Term Voltage Instability Using a Digital Faster Than Real-Time Replica

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***Abstract*—This article describes the use of real-time co-simulation platform in detecting faults and predicting the dynamic behaviour for the resilient operation of future smart grid systems. The fault detection part of the platform is implemented using a quick change detection algorithm and post-fault dynamic behavior prediction is done using faster than real-time simulations. The proposed method is implemented for a WECC three machine nine bus system and the performance is analyzed.**

Keywords – Real-time Simulation, Faster than Real-Time Simulation, Fault Induced Dynamic Voltage Recovery(FIDVR), Composite Load Model(), Under Voltage Load Shedding (UVLS).

I. Introduction

Smart grids integrate physical infrastructure, information and communication technology, and market mechanisms with policy regulations and business processes. Assessing the resiliency of such a system of systems requires new methods and tools, since existing ones typically focus on one of the subsystems and their particular mathematical properties.

Co-simulation dynamically links numerical models of different nature in order to execute them concurrently. The challenges that rise from such a combination are manifold: execution performance, description language interoperability, solver synchronization, scenario handling or unsteady parameter spaces make working with this method hard. However, the benefits are compelling: machine-supported optimization of complex situations, risk-assessment or cyber-physical infrastructure, or scenario generation and evaluation are powerful tools in making our power system more reliable.

This article describes the use of real-time co-simulation platform in identifying and responding to faults in the power system. Fault detection in traditional power systems is confined to the detection of loss of a significant component (e.g., a transmission line, load, generation unit) using information from protection devices and other traditional supervisory control and data acquisition(SCADA) elements. The time scale required is in the order of a few second up to several minutes.Modern wide area protection and control (WAMPAC) systems offer much quicker time scales, but fail to automatically detect the catastrophic cascading effects associated with some faults, which may even lead to a system black out. They rely on the control room operator knowledge to solve this problem in time.In this article addresses the above problem is addressed in a smart grid paradigm, where we expect the electricity grid to develop more towards a self-healing grid and proposes automated fault detection and response.

In this paper we focus particularly focus on the short term voltage instability problems such as the fault induced dynamic voltage recovery(FIDVR). The main characteristics of this FIDVR phenomena is that they occur in a time frame of few seconds most often less than 30 seconds. The FIDVR is most recently encountered problem by many power utilities throughout the world [1]–[4] mostly during the mid summer climatic condition, when there is increased penetration of air conditioners(AC) load in the power system. During an FIDVR phenomena a low voltage sag at the load bus due to the clearance of a severe fault like transmission line fault. This voltage sag induces a stalling behaviour in the induction motors present in the system. The stalling behaviour results in huge reactive consumption by these induction motor loads and is about 5-8 times the normal reactive power requirement. Thus further resulting in the delayed voltage recovery. This delayed voltage recovery may result in rapid tripping of other loads and even lead to collapse of an entire area of power system.

The mitigation strategies such for delayed voltage recovery problem can be divided into categories such as supply side control solutions [6]–[8] and demand side control solutions [9]–[13]. The supply side control solutions focus on the mitigation of FIDVR by providing the required dynamic reactive power support from adequate supply sources. The mitigation stratergy implemented is the optimal placement [6] of reactive power sources such as dynamic var reserve of local gerenators,shunt capacitors or advanced dynamic var compensators to provide required reactive power support to the system. But the large scale installation of such big systems are not economically viable as their cost increase with the size(reactive power capacity). Supply side management methods act as a solution for mitigation of FIDVR problem, but it should be implemented in the planning and development stages of the system. Hence when it comes to real time mitigation of the FIDVR event during the system operation only very few methods exsist in the literature such as dynamic control of distributed generators like PV systems [7]. Demand side control problems relies on adequate shedding of loads to provide the dynamic reactive power support and under voltage load shedding(UVLS) [10] is a widely used to method in this aspect. Many variants of under voltage load shedding have been proposed in the literature over the past few year and can be classified in terms of features [10] as centralised [11], [12] or decentralised [9], static or dynamic , closed or open loop , algorithmic rule based or decision based. Under all the features considered the main focus of an intelligent UVLS scheme is to shed the lowest possible amount of load. For this purpose, its crucial to decide on the key aspects such as time, amount and location of load shedding to be done for a particular FIDVR phenomena happening. The exact modeling of system plays a crucial role in the analysis of the system behaviour during an FIDVR, especially the load dynamics is very important in the accurately capture the events. The period of concern here is in the order of seconds, and time domain simulation can only exactly capture the system dynamic during the event. In-order to develop a better UVLS scheme for the mitigation of FIDVR event, it is of utmost importance to exactly capture the system dynamics and time domain simulation of detailed model of the system acts as an important tool for the same propose.

In this paper we propose the use of a digital twin that can accurately and efficiently model the model system dynamics and predict the FIDVR event. Our solution relies on the ultra-fast time domain simulation of the real system model. The high level of details allow us to accurately describe the FIDVR event propagation and ultra fast simulation allows us to take action fast enough to possible damage from the FIDVR event, including elements.

The rest of the article is divided into five main sections. The section II gives the basic description of the real-time co-simulation platform developed. Section III explains the QCD implementation for the line outage detection and section IV describes the QCD implementation in a WECC three-machine nine-bus system. Section V explains the use of the real time co-simulation platform for post-fault dynamic behaviour prediction of the system. Section VI concludes the paper with discussion and future scope of the work.

II. Faster than Real-Time Digital Twin (FTRDT)

A faster than real-time digital twin, as shown in fig. 1, is developed with a Python based master algorithm controlling three different functional units. The first unit is a real time transmission network simulation, implemented in RTDS, using the RSCAD software. The PMU component of the RSCAD software is used to obtain the magnitude and angle of the bus voltage of the nodes of interest of the transmission network.

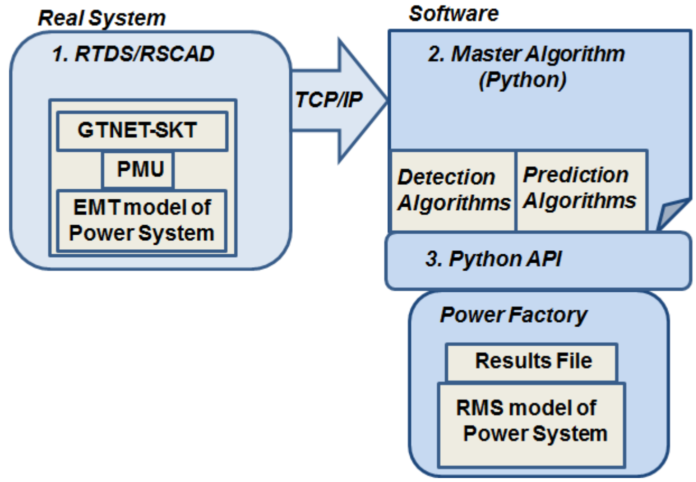

Fig. 1. Interface diagram

The GTNET-SKT card is used to stream this measurement data as TCP/IP packets. This simulation provides the measurement data in real-time emulating the infeed of measurements to the control room. The second unit contains different fault detection and prediction algorithms, which process the real measurement data and simulation results of the same system providing predictions on the post-fault dynamic behavior of the system associated with a fault detection. The third unit consist of time domain simulation model (RMS/phasor simulation model) of the same transmission network re-configurable to different post-fault scenarios based on the detection algorithm output, simulated using the PowerFactory software running in engine mode and capable of producing faster than real-time simulation results. The simulation results of PowerFactory model is stored as a ElmRes object, and can be accessed by the master algorithm for further processing. The ElmRes object consist of all the variables monitored as a result of PowerFactory model simulation and is stored in tabular form as time series data. The number of these variables monitored plays a crucial role in the time taken by the PowerFactory Model simulation, as the PowerFactory engine takes time to process and the store the ElmRes object file.

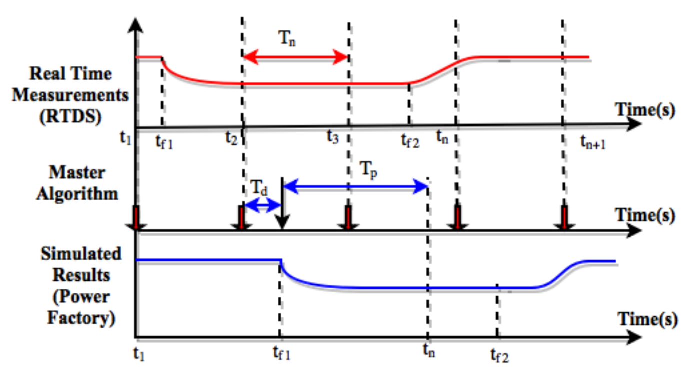

Fig. 2. Timing diagram

The operation of the faster that real-time digital twin can be

TABLE I
TIME TAKEN FOR 5 SEC SIMULATION WITH .001 SEC STEP SIZE FOR VARIOUS POWERFACTORY MODEL SIMULATION

PowerFactory Models	RMS	EMT
9-bus system	Init = 2.82 sec Dyn = 0.25 sec	Init = 2.78 sec Dyn = 2.92 sec
39-bus system	Init = 2.88 sec Dyn = 1.38 sec	Init = 2.75 sec Dyn = 16.22 sec

explained using the timing diagram as shown in fig. 2. The first part of the timing diagram shows the real-time measurements obtained by the master algorithm from the RTDS T_n as the time taken to obtain n samples of the PMU data with sampling rate of n samples per second. Each data contains the bus voltage magnitude and angle values along with their time stamp. This data is processed by the fault detection part of the master algorithm as shown in the second part of the timing diagram. The T_d denotes the maximum time taken for the detection algorithm to detect a fault. So a fault happening in the system at t_{f1} is detected only after $T_n - t_{f1} + T_d$ and the PowerFactory model is updated with fault detail at this time by the prediction algorithm as shown in the third part of the timing diagram. In the next step, the PowerFactory model is simulated for time T_p till the next fault is detected in the system at t_{f2} seconds.

The table I shows the time taken for 5 second simulation of various PowerFactory models with a step time of .001 seconds. The time taken for each type of simulation is represented as sum of two terms where the first term denotes the time taken for initialization of the PowerFactory Engine and loading a particular model and the second term denotes the time taken for dynamic simulation of the model. The RMS simulation models which is basically a simplified model of actual system is able to provide faster than real-time simulation results. This can be noted from the table I. The PowerFactory models are simulated with higher values of simulation step-size ($>$ 0.001 sec) to have a faster than real-time simulation. All the simulation are run from a personal computer with configuration DELL i7, 2.6 GHz(4 CPU's), 8 GB RAM. Thus, by properly selecting the factors such as type, size, step-size, no of monitored variables of PowerFactory simulation model, we have a possibility of having a faster than real-time PowerFactory simulation.

A. *FIDVR predictive mitigation using FTRDT*

The main porposs of the detection algorithm is detect any topological changes that can lead to the occurrence of an FIVDR event.In the present study we confined ourselves to line outage detection which can lead to FIDVR event. We use the quickest change detection (QCD) using the Cumulative Sum(CUSUM) algorithm developed [16] for the detection of outage of line and explanation of implementation of the same is beyond the scope of the paper. The prediction algorithm implementation is activated with the detection of an FIDVR event by the detection algorithm. The prediction algorithm starts the different time domain simulation of FIDVR event for a 5 seconds simulation time and different scenarios of UVLS schemes for the present fault. Thus the deciding factors such as the location , amount and time of load shedding is critically selected for each of this case and the simulation result is obtained for all the scenarios with a time very less than 2 seconds. A simple merit based analysis is used to choose the best UVLS scheme from the each of the simulated scenarios. The chosen UVLS is further implemented in the actual system for the mitigation of the FIDVR.

III. MODELING OF AN FIDVR EVENT WITH UVLS SCHEME

This section describes the modelling of a FIDVR event using the composite load model and further explains the UVLS scheme implementation for a test system . The test system as shown in fig.3 is developed as in [3] , using the PowerFactory software. The Buses 3,4 of the test system having are having static loads and the composite load model is connected the bus 4.

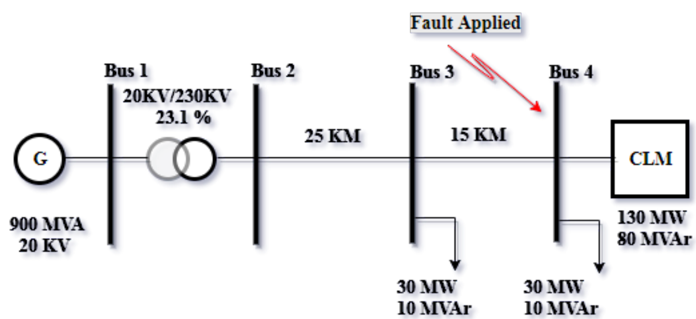

Fig. 3. Test system for FIDVR modeling

A 3 fault is applied at Bus 4 at around one second of the simulation time and is cleared at around .4 seconds, which triggers the delayed voltage recovery in the test system. The FIDVR event is mainly caused by the composite load model in response to 3 phase fault not cleared in less than 3 cycles. The UVLS scheme is implemented inside the composite load model block . The following subsections further explain the composite load model and the UVLS scheme.

A. *Composite Load model*

The composite load model for the present work is a slightly modified version of actual model explained in [14] . The main focus of the present work is to create the delayed voltage response resembling an FIDVR event and hence only few load models are used. The 3 phase induction motor model collectively represent by motor C and D along with other load model such as PV system model are not used in the present study. The figure 6 shows the composite load model implementation for the present study . The parameter of different components are mostly obtained for [15] and modified for the sake of better illustration of the FIDVR behavior. The each component of the composite load model is modeled in the PowerFactory software using the constant impedence load model. The Motor A,B models tough they differ in the post stating behavior, they collectively represent the load behavior of many single phase residential air conditioning RAC system. The residential air conditioner loads are the major cause of the delayed voltage response and their behavior can be modelled by algebraic equations as describes in [14] . For the present study the stalling behavior was characterized by this load consuming around 1.65 times the actual active power and 5 times the reactive power consumption as shown in the figure4.The figure5electronic load model is similar to a low voltage ride and is characterized by the following equations as in [13] . The present work don't exactly model the thermal relay and contractor characteristics of the RAC systems.Both the Motor A,B load and electronic load are modeled using the composite frame of the PowerFactory software which gives active and reactive power set points to a constant impedance load. The static load is modeled in a simple zip load model.

```
if V > 0.86:
        P  =  Po
        Q  =  [Q'o + 6 * (V - 0.86)^2 ]
if V < 0.86 and V > V'stall:
        P  =  [Po +  12 * (0.86 - V)^3.2 ]
        Q  =  [Q'o + 11 * (0.86 - V)^2.5 ]
if V < V'stall:
        P = Gstall * V * V
        Q = - Bstall * V * V
if V < Vstall and t > Tstall
        P = P0*1.65
        Q = Q0*5
```

Fig. 4. Control logic implemented for Motor A and B model

```
if (V < Vmin)
        Vmin = V
if( Vmin < Vd2 )
        Vmin = Vd2
if( V < Vd2 )
    Fvl = 0.0
else if( V < Vd1 )
    if( V <= Vmin )
        Fvl = (V - Vd2)/(Vd1 - Vd2)
    else
        Fvl = ( (Vmin- Vd2) + frcel * (V - Vmin) ) / (Vd1 - Vd2)
    endif
else
    if( Vmin >= Vd1 )
        Fvl = 1.0
    else
        Fvl = ( (Vmin - Vd2) + frcel * (Vd1 - Vmin) )/ (Vd1 - Vd2)
    endif
endif
Pel = Fvl * Pel0
Qel = Fvl * Qel0
```

Fig. 5. Control logic implemented for electronic load model as specified in [14]

The figure 6 illustrates the FIDVR event modeled for present study using the composite load model.As seen from the figure the delayed voltage response during the FIDVR event is more predominant in the bus close to the composite load and at low voltage level bus.

B. UVLS scheme for FIDVR event

The figure.8 illustrates an UVLS scheme similar to the existing stage based UVLS schemes implemented in decentralized relay. The figure.8 the zoom in of the 0-5 second time period of the figure.8. From figure.8 it is clearly visible that a stage based UVLS scheme of 5 percentage of load shed with every .5 seconds starting from 2.5 seconds doesn't mitigate the FIDVR event. For the predictive mitigation of the FIDVR event, the paper presents an algorithmic decision based method of UVLS scheme. A predictive algorithm formulates a decision based on faster than real time simulation result of 5 seconds of different stage based load shedding scheme and the next section illustrates how this is done using digital twins for different load shed shedding schemes.

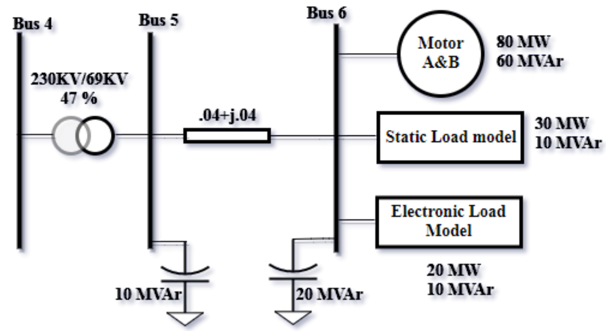

Fig. 6. Composite load model as specified in [14]

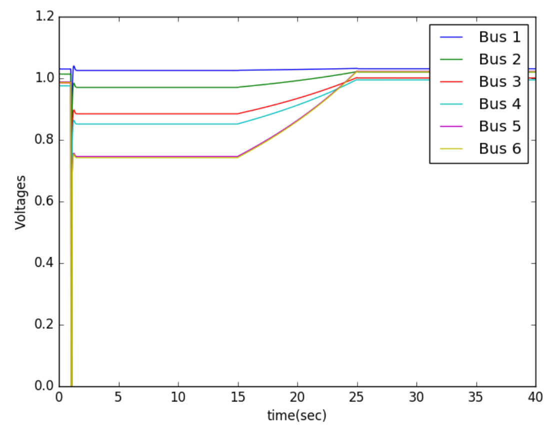

Fig. 7. Composite load model as specified in [14]

IV. SIMULATION RESULTS

The figure 10 illustrates the UVLS load shedding scheme proposed for the present work

V. CONCLUSION

1.Time of computation
2.number of twins
3.selecting criteria

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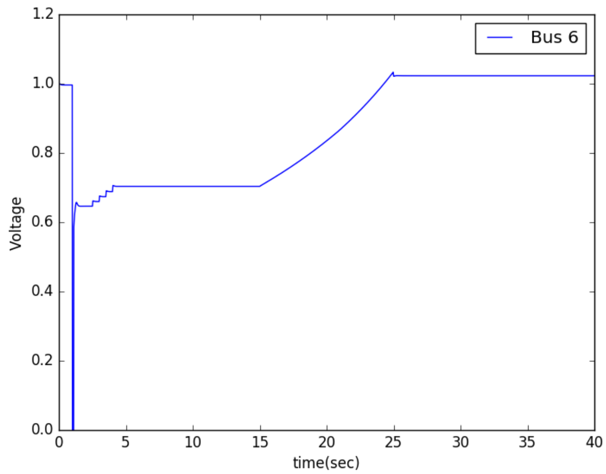

Fig. 8. Stage based UVLS Scheme

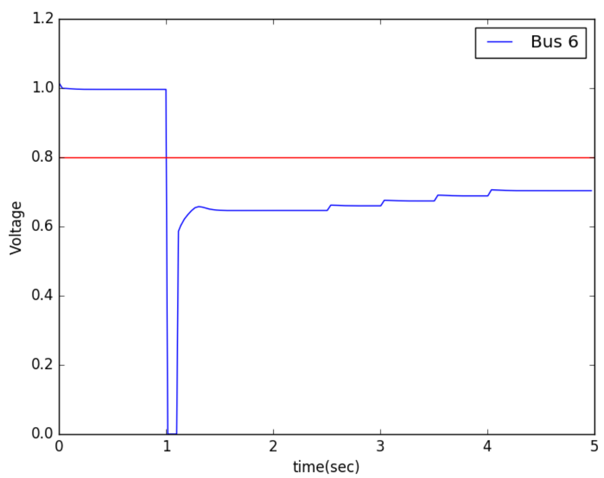

Fig. 9. UVLS Scheme

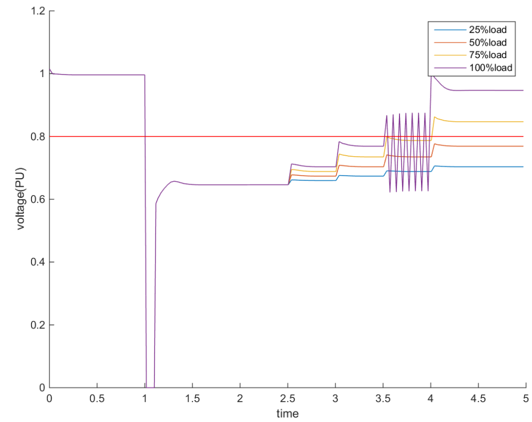

Fig. 10. UVLS Scheme

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