Designing a Microgrid Test System for Transient Analysis

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***Abstract*— A power system test system is designed using PSCAD/EMTDC software for transient analysis, which can be specifically used for transient studies with Distributed Generators (DGs) or this system can be easily developed as a Microgrid test system. The model is developed based on a section of a practical power system that is Kukuleganga area of the Sri Lanka power system. This includes 132kV transmission system, Kukuleganga hydro power station, five grid substations with 33kV distribution buses and DGs. The developed model is verified through comparing the actual fault data obtained from the Ceylon Electricity Board, Sri Lanka with the results obtained from the developed PSCAD/EMTDC model. The Discrete Wavelet Transform is used to identify the degree of accuracy in verification of the model. The test results are demonstrated for both current and voltage waveforms.**

Keywords*— discrete wavelet transform; distributed generators; microgrid test system; PSCAD/EMTDC; transient analysis.

I. INTRODUCTION

A. Transients in Power System

Transients occur as a response to any change of the equilibrium of the system. Change of the equilibrium might be caused by a step input or an impulse input [1].

In a power system, transients may occur due to different reasons, such as: faults, tripping off loads, tripping off generators, operation of circuit breakers, capacitor switching and motor starting. Transient behavior of a power system depends on different factors. Incident point of the cycle, distribution of the loads, distribution of generation and flow of power in transmission lines are the considerable factors that affects transient behavior of the power system.

PSCAD/EMTDC is a strong platform for transient analysis of power systems. There are different benchmark test systems available for transient analysis of transmission systems and few for distribution system transient analysis[2]. Different test systems have been used as microgrid test systems [3] in researches, but authors were unable to find a verified microgrid test system for transient analysis. This paper presents a power system model based on an actual power system for transient analysis. The test system is verified with actual transient data in PSCAD/EMTDC. This test system can be used for transient analysis with distributed generators or can be further developed as a microgrid test system. The particular actual power island selected is a part of the Sri Lankan Power System based on the Kukuleganga hydro power station [4].

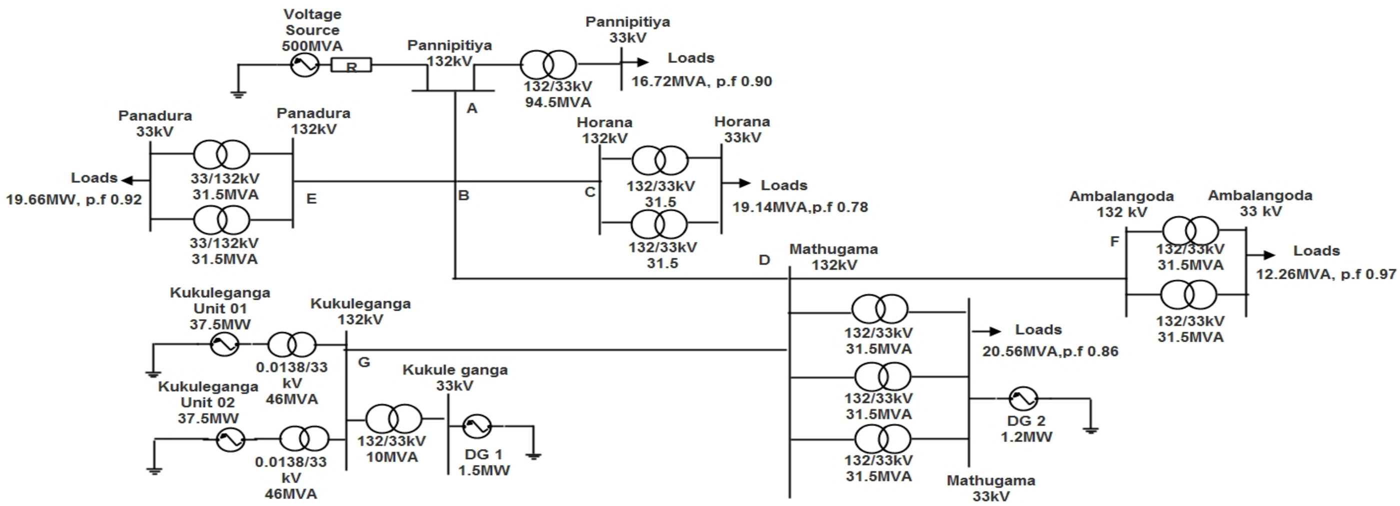

Fig. 1. Single Line Diagram of the Selected Power Island.

The system shown in Fig. 1 runs stable in steady state operation. The balance of active and reactive power generation and consumption can be described as follows. The sum of total installed loads (consumption) is 190.581 MW with 55.560 MVar. The total generation is 193.133 MW with 57.320 MVar (where 118.610 MW with 32.619 MW are from the voltage source and the rest are from DGs and Kukuleganga generators). The small difference between generation and consumption is due to the losses in transmission lines and slight deviation of voltage from its rated value at receiving end.

B. Kukuleganga Power Island

The model is developed based on the section of the Sri Lanka Power system, which centralizes the Kukuleganaga hydro power station. The single line diagram of the selected power island is shown in Fig. 1 Kukuleganga has two generators of which each is 37.5MW. The power generated at Kukuleganga is transmitted to the Mathugama Grid Substation (GSS) through a double circuit 132kV transmission line. Mathugama GSS has three 31.5MVA, 132/33kV transformers. The main 132kV feeder from Pannipitiya GSS through Panadura & Horana Grid Substations has connected to Mathugama bus and another 132kV line is also extended to Ambalangoda GSS. The most important fact to choose Kukuleganga area for the purpose is because the above mentioned power system can be disconnected from the remaining part of the national power system through only one breaker (Mathugama-Pannipitiya132kV transmission line at Pannipitiya GSS).The operation of the breaker can result to create a power island when it isolates Mathugama transmission line from the Pannipitiya GSS end [4]. Also there are several DGs connected in this area and has a diversified load, including residential and industrial customers.

II. Test System Modelling

PSCAD/EMTDC simulation software was used to model the test system.

A. Generator Models of Kukuleganga Power Station

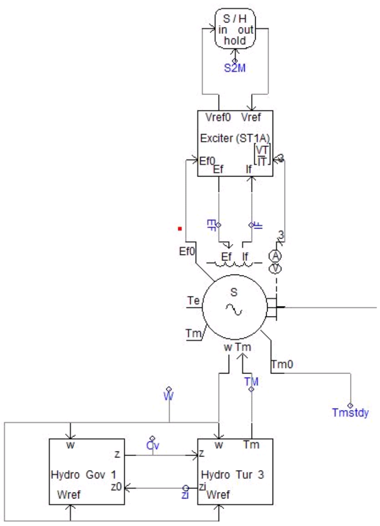

Fig. 2. PSCAD/EMTDC Model of Kukuleganga Unit 1.

TABLE I. Generator, Turbine and Governor Parameters

	Parameter	Values
Generator	Generated RMS Voltage (L-L)	13.8 kV
	Rated RMS Line Current	1.758 kA
	Inertia Constant (H)	3.5 s
	Armature Time Constant (T_a)	0.332 s
	X_d, X_d', X_d'', X_q, X_q', X_q''[pu]	1.014, 0.314, 0.28, 0.77, 0.228, 0.375
	T_{do}', T_{do}'', T_{qo}', T_{qo}'' [s]	6.55, 0.039, 0.85, 0.071
Turbine	Tunnel water starting time	1.0 s
	Turbine Damping Constant (D)	0.5 (p.u)
	Penstock Head Loss Coefficient	0.02 (p.u)
Governor	Permanent Droop (Rp)	0.05 (p.u)
	Temporary Droop (Rt)	0.04 (p.u)
	Pilot Valve and Servomotor Time Constant (Tp)	0.05 (p.u)
	Main Servo Time Constant (Tg)	0.2 s
	Dead band Value	0.02(p.u)

Kukuleganga is a run-off-the-river type hydro power plant having two 37.5 MW rated generator units. The standard synchronous generator, hydro turbine and governor models available PSCAD/EMTDC are connected as shown in the Fig. 2 to represent one unit of the power station. The models are configured according to hydro power station plant data. For unavailable data, typical values for a generator of the same capacity were used [5]-[6]. The machines are driven in droop control mode for all the simulations shown in this paper. Table I presents some of the important parameter values used to configure the generator, turbine and governor models.

B. Distributed Generators (DGs)

There are several DGs are connected to the 33kV feeders in the actual system [4]. There is a mini hydro power plant of 1.2 MW connected to the 33kV feeder from the Mathugama GSS and there is another 1.5 MW mini hydro connected to the Kukuleganga 33kV bus. These mini hydro power plants are modeled using the synchronous generator with a constant mechanical torque and the standard IEEE exciter model AC1A is used as the exciter. Generators are configured using typical data for same capacity standard generators [5]-[6]. Grid connected solar PV systems will be integrated into the system in future developments.

C. Transmission Lines

The power system model has six segments of 132 kV transmission lines. Since the test system is designed for transient analysis, it should be able to behave accurately at higher frequencies. Among the different models available, the frequency dependent (Phase) model is used. It is the most accurate time domain model available in PSCAD/EMTDC representing the full frequency dependence of all line parameters [7]. PSCAD/EMTDC employs a separate block to define the mechanical parameters of the transmission lines. Therefore, the transmission line model is configured and applied accordingly to represent double circuit transposed transmission lines with appropriate conductor sizes for all six segments. The transmission line parameters are given in Table II.

TABLE II. TRANSMISSION LINE PARAMETERS

Line (positive sequence)	**R_1 [pu]**	**X_1 [pu]**	**B_1 [pu]**
AB (12.3 km)	0.00629	0.02734	0.0063
BC (20 km)	0.00872	0.0444	0.01041
BE (4.7 km)	0.0048	0.01082	0.00288
BD (28.1 km)	0.01437	0.06245	0.0144
DG (32 km)	0.03065	0.06904	0.01461
DF (28 km)	0.012208	0.002221	0.02079
Line (negative sequence)	**R_2 [pu]**	**X_2 [pu]**	**B_2 [pu]**
AB (12.3 km)	0.0196	0.0946	0.0035
BC (20 km)	0.0345	0.1482	0.006
BE (4.7 km)	0.0106	0.0355	0.0014
BD (28.1 km)	0.0485	0.2082	0.0085
DG (32 km)	0.0669	0.2259	0.0087
DF (28 km)	0.0483	0.2074	0.0085

D. *Voltage Source Representation*

In an actual power system, transient signals can be generated due to various phenomena as discussed in section I.A. These generated transients may contain different frequency components for different phenomena. However, in transient analysis the most predominant frequency band is in the range of kHz [8]. The inertia of the machines of the power system will not have considerable impact on high frequency transients (in kHz range) [9]. Therefore, the remainder of the power system can be represented as an infinite bus and, a voltage source with appropriate impedance according to the fault level is used in the simulation. Table III presents the parameter values used in configuring the voltage source, the infinite bus.

TABLE III. VOLTAGE SOURCE PARMETERS

Parameter	**Values**
Voltage (kV)	132 kV
Impedance (Ω)	$12.94188 < 87.5^0$
Frequency (Hz)	50 Hz

E. *Transformers*

Three phase two winding transformer available in PSCAD/EMTDC is configured accordingly to represent the transformers where necessary. The specific parameter data for the different rated transformers shown in Fig. 1 is given in Table IV [7]. 132/ 33 kV transformers in this power system have on-load tap changing ability. A change in tap setting is modeled as a change in the turns-ratio of the transformer [7]. Logic is developed to change the taps to regulate the secondary voltage in the event of increase or decrease of primary voltage. As an example for a 132/33 kV turns ratio, tap changer can regulate the secondary voltage, when primary voltage is varying in the range from 115.5 kV to 148.5 kV.

TABLE IV. TRANSFORMER PARAMETERS

13.8/ 132 kV, 46 MVA YΔ transformer	
Parameter	**Values (p.u.)**
Leakage Impedance	0.04428
Copper Loss	0.0036956
132/ 33 kV, 31.5 MVA YΔ transformer	
Parameter	**Values (p.u.)**
Leakage Reactance	0.04191
Copper Loss	0.0043084

F. *Loads*

The station supply load at Kukule ganaga Power plant and other substations are modeled as constant impedance loads and it is not specified in the single line diagram. All the other loads are considered as constant power loads. Values of the constant power loads are shown on Fig. 1.

III. MODEL VERIFICATION

The developed PSCAD/EMTDC power system model has to be verified to be used as a test system for transient analysis. Therefore, the system verification was done by using a set of actual data at a power system fault taken from the Ceylon Electricity Board. The same situation was simulated using the developed test system in PSCAD/EMTDC and the simulated results were compared against the actual data. Respective current and voltage waveforms for the two cases were considered.

The fault scenario was a line to ground fault occurred in Y-phase at Mathugama GSS. Actual voltage and current data were taken by a Digital Fault Recorder (DFR) at the Mathugama GSS.

A. *Instantaneous Voltage and Current Waveforms*

The above mentioned fault scenario was simulated in the developed PSCAD/EMTDC model and the three phase voltages and currents were measured. In order to simulate a similar condition at the time of the fault in PSCAD/EMTDC model, load distribution and generator loadings of the actual power system by the time of the fault occurrence were used in the simulation. Plotting frequency of 6.4 kHz and solution frequency of 50 kHz (solution time step of 20 µs) were used in the PSCAD simulations as the sampling frequency of the actual waveform was 6.4 kHz.

Fig 3 shows a comparison of the simulated and actual voltage waveforms of the three phases during the fault. Fig. 5 presents a zoomed view of the compared voltage waveforms of Y-phase. It shows that the simulated data highly matches with the actual data.

Similarly, Fig. 4 shows the comparison of the simulated and actual current waveforms of the three phases. Fig. 6 is a zoomed view of the compared current waveforms of Y-phase during the fault, which further verifies that the simulated data matches with the actual data.

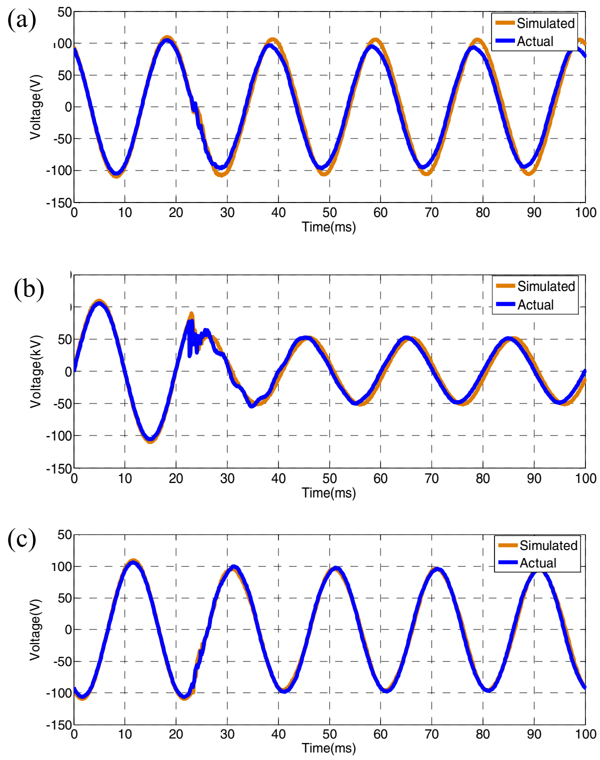

Fig. 3. Comparison of the simulated and actual three phase voltages measured at Mathugama Bus . (a)R-Phase (b) Y-Phase (c) B-Phase.

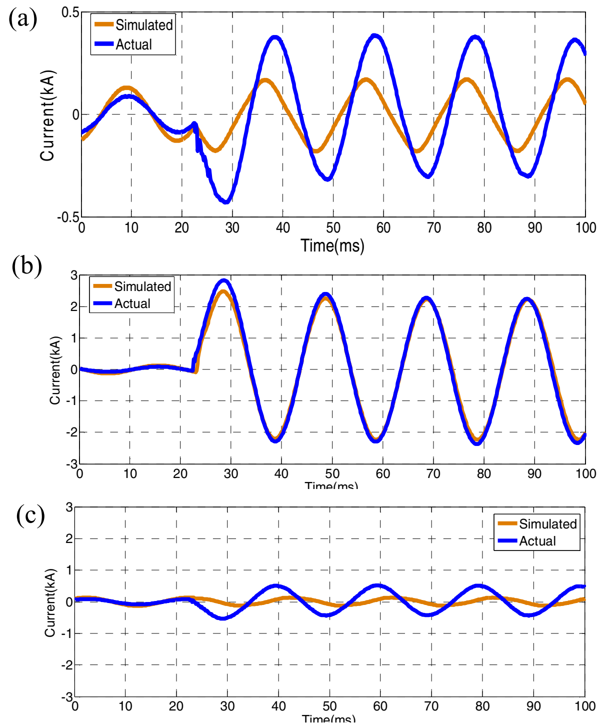

Fig. 4. Comparison of the simulated and actual three phase currents measured at Mathugama Bus. (a)R-Phase (b) Y-Phase (c) B-Phase.

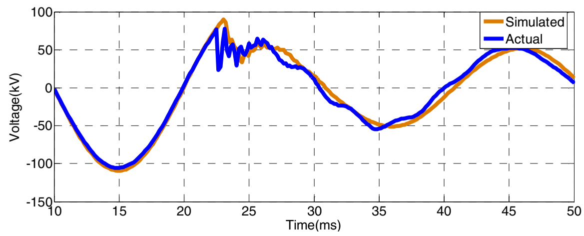

Fig. 5. Comparison of the simulated and actual voltages of Phase-Y measured at Mathugama Bus (Zoomed).

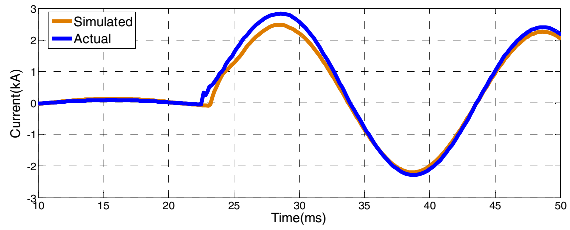

Fig. 6. Comparison of the simulated and actual currents of Phase-Y measured at Mathugama Bus (Zoomed).

B. Discrete Wavelet Transform (DWT)

Wavelet transform is used to decompose a signal into several signals in different frequency bands. These signals are known as wavelet coefficients. Here, the wavelet coefficients are in terms of the mother wavelet. Discrete Wavelet Transform (DWT) is a signal processing technique that is widely used to analyze discrete signals. Here, the discrete domain waveform is passed through successive high pass and low pass filters to taken out the wavelet coefficients [10]-[11]. DWT of a discrete signal can be defined mathematically as follows:

$$\Psi_{m,n}(t) = \frac{1}{\sqrt{a_0^{\ m}}}.\Psi\left(\frac{t - nb_0 a_0^m}{a_0^m}\right) \tag{1}$$

Where $\quad a = a_0 \,, \quad b = nb_0 a_0^m$

The corresponding discrete wavelet transform is given by,

$$DWT_{\Psi}.f(m,n) = \Sigma_k .f(k).\Psi^*_{m,n}(k) \tag{2}$$

C. DWT Module in PSCAD

The DWT model available in PSCAD/EMTDC is built based on the Mallat Tree Algorithm for Wavelet Decomposition. This principle can be represented as shown in Fig. 7 [11].

DWT module in PSCAD allows the user to select various initial input parameters, such as level of filters, the mother wavelet and the sampling frequency. According to the given level, it generates output waveforms of set of low and high pass filters, which gives the DWT of the given waveform. The output of each high pass filter is denoted by D_n (n=1, 2, 3...) and output of low pass filter is given as the input to the next level of filter. The low frequency output of the leftmost filter is denoted by output A.

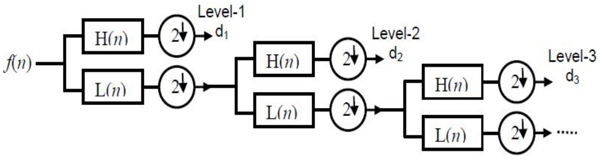

Fig. 7. Mallat Tree Algorithm.

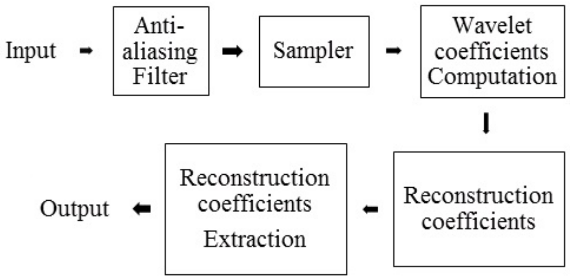

Fig. 8. Block diagram showing the Discrete Wavelet Transform[11].

The Discrete Wavelet Transform generation process used in the PSCAD model can be shown as in Fig. 8 [11]. Detailed information on DWT can be found in [12]-[14].

D. Analyzing Power System Transients with DWT

Transients are non-stationary signals and they have to be analyzed using special waveform analyzing methods such as Short Time Fourier Transform (STFT) or Wavelet Transform (WT) methods. But, Fourier based methods employs fixed frequency and time resolution through fixed size windows. In contrast to that, wavelet transform based methods employs windows with varying height and width [14]-[15].Therefore, we can have higher time resolution with lower frequency resolution or vice versa using wavelet transform. Further, it is easy to express disordered transient signal in terms of a disordered mother wavelet than in terms of an ordered symmetrical sinusoidal signal.

E. Verifying Developed Model Using DWT

The developed power system model was further verified by using the DWT on transient signals. Therefore, using the Discrete wavelet transform (DWT), the original current and voltage waveforms were decomposed to different wavelet coefficients. The signal is sampled at 3 kHz and Daubechie's 4 (Db4) mother wavelet was used and the waveforms were analyzed for four decomposition levels of DWT.

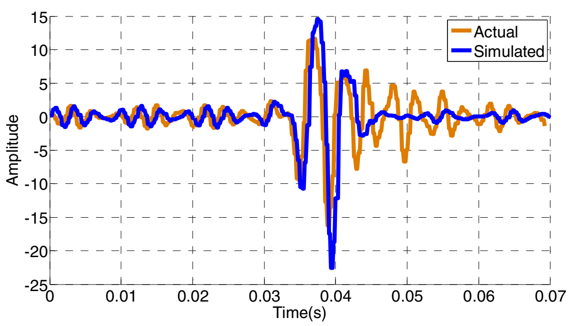

Fig. 9. Comparison of DWT decomposition level 3 (D3) of actual and simulated voltage waveforms.

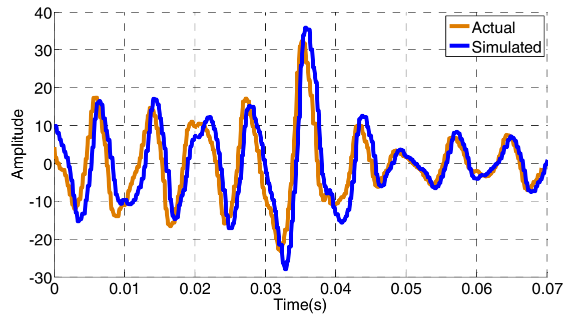

Fig. 10. Comparison of DWT decomposition level 4 (D4) of actual and simulated voltage waveforms.

High frequency coefficients are ignored, considering the significant effect of noise on high frequency signals of the actual waveforms. The comparisons of outputs of DWT decomposition levels 3 and 4, which are in the frequency bands of 187.5 Hz to 375 Hz and 93.75 Hz to 187.5 Hz respectively of the actual and simulated voltage waveforms, are shown in Fig. 9 and Fig. 10 respectively. It can be observed that both the DWT decomposition level 3 (D3) and level 4 (D4) signals of voltage waveforms of the actual and simulated systems match to a higher degree.

Similar responses can be identified in comparing the DWT decomposition levels 3 and 4 of current waveforms of actual and simulated systems.

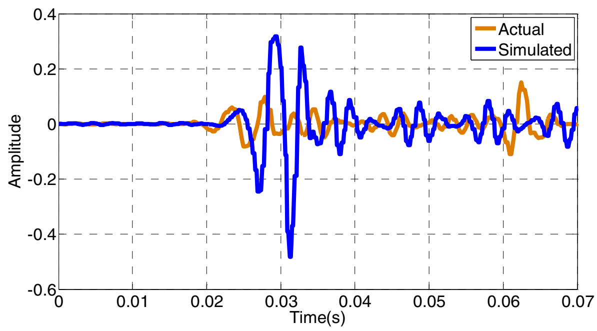

Fig. 11. Comparison of DWT decomposition level 3 (D3) of actual and simulated current waveforms.

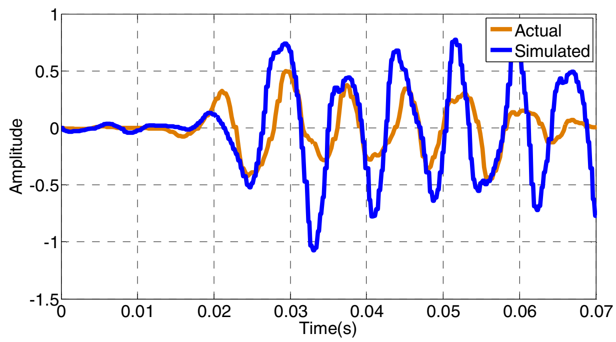

Fig. 12. Comparison of DWT decomposition level 4 (D4) of actual and simulated current waveforms.

Fig. 11 shows the comparisons of outputs of DWT decomposition levels 3 (D3) of the actual and simulated current waveforms and Fig. 12 presents it for the decomposition level 4 (D3). Fig 12 indicates that D4 signals of current waveform have a similar pattern, but D3 signal in Fig. 11 presents some clear differences in the response.

These differences identified in the comparison of voltage and current waveforms of actual and simulated systems can happen due to different reasons. The following were identified as possible major reasons:

1. In simulating the fault, fault impedance and the incident time were estimated to match with the actual current and voltage waveforms but, still the simulated values can be different.
2. In modeling the test system, power electronic applications such as grid connected solar PV systems were not included and thus, the possible effect of harmonics is not represented in the simulated case.
3. Industrial loads were represented as constant power loads ignoring the electro mechanical behavior of motors that may have significant effect in transient situations.
4. System was simulated as a balanced system, prior to the fault, which may have been unbalanced in the actual system.

Considering the above facts and figures, it can be agreed that the designed test system presents an acceptable accuracy for transient analysis having DGs, which can be further developed as a microgrid test system by introducing appropriate generator controls and demand side management and by integrating other DGs, such as Solar PV, wind and different load models.

IV. APPLICATIONS

The PSCAD/EMTDC model developed can be used for different transient analysis studies, such as:

1. Fault studies: detection and/or location
2. Protection coordination in a microgrid or with DGs
3. Effect of transformer inrush currents on protective relays in an islanded system
4. Effect of capacitor switching under different phenomena
5. Islanding detection
6. Test any novel technique based on transient signals of power systems

With the enhanced interest in microgrids and smart grids, the developed power system test system can be very useful for future research. It can be further developed as a benchmark test system of a microgrid by introducing different DGs with an appropriate energy management system and by developing the detailed load models with demand side management.

V. CONCLUSIONS

A detailed power system test system based on an actual system was developed and verified against actual data. The test system was specifically designed for transient analysis and it can be used as a microgrid test system having DGs. The simulation results showed very high level of agreement with the actual data when the voltage and current waveforms were compared for a real faulty situation of the power system. The comparison of waveforms using DWT further confirmed the accuracy of the designed test system. The test system can be a versatile tool for researchers in transient analysis specifically in microgrids or smart grids.

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