Uncertainity and Disturbance Estimator based Control of Transformerless DVR

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***Abstract*—** This paper presents Uncertainty and Disturbance Estimator (UDE) based control for Transformerless Dynamic Voltage Restorer (TDVR). The proposed UDE based control algorithm for TDVR mitigate the voltage disturbances and maintain robustness during parameter (filter) variations. The control equation of UDE is derived based on the dynamic model of a voltage source inverter along with the LC filter. The proposed UDE control estimates the uncertainties and disturbances by an appropriate filter (loop filter involved in the derived UDE control law) and used for further synthesis, thus accounts for robustness. The simulation studies are performed for 230 V low voltage (LV) system in MATLAB to verify the efficacy of UDE control for symmetric and asymmetric voltage sags along with the parameter mismatch (inverter filter) conditions.

Keywords—TDVR; UDE; voltage sag; parametric variation;

I. Introduction

For the past decade usage of voltage sensitive load equipment has increased in industrial applications and as well in the domestic applications (home appliances) which are creating serious problems related to the quality of power delivered [1]. Of these, the prominent issue is voltage quality problem which is in the form of voltage sags, harmonics and swells which can cause severe process disruptions and results in substantial economic/data loss. The Dynamic Voltage Restorer (DVR) which is a custom power device [2]- [4] is installed in the distribution system to protect the sensitive loads from voltage quality problems. The conventional DVR injects the compensating voltage in series with supply voltage using injection transformer thus maintaining load voltage at desired value. However, many issues viz., weight, losses, cost pertaining to injection transformer constraints [5] the application of conventional DVR in places like commercial buildings, offices etc., Thus to overcome these constraints [5], [6] proposes Transformerless DVR (TDVR) topology. The TDVR topology employs filter capacitor instead of transformer which is connected in series between the grid and load as shown in Fig.1.

The main challenge with TDVR topology is design of control structure. In [7] predictive control technique is adopted for TDVR to compensate the voltage disturbances. In this method the prediction of the reference capacitor voltage is essential which is dependent on the filter parameters. Therefore, the performance of the predictive control is subject to degradation when the reference capacitor voltage prediction is not accurate due to the variations in the filter parameters. In [8] sliding mode control (SMC)scheme is proposed for TDVR. Though SMC is independent to parameter variations but it suffers from chattering phenomenon and moreover involves computational complexity. Uncertainty and Disturbance Estimator (UDE) based control method was proposed in [9]-[12], which has good abilities of reference tracking, uncertainty and disturbance rejection. It is considered as a replacement of the time-delay control. The UDE-based control method is based on the assumption that, by using an appropriate filter, an unknown continuous band-limited signal can be estimated thereby making it a practical robust controller. The design procedure is simple as the accurate model of uncertainties and external disturbances is not required. Thus owing to its advantages and non-complexity this paper proposes UDE based control of TDVR for compensating voltage disturbances.

During unbalance grid conditions, harmonic ripple is observed in *dq*- voltages of a conventional SRF-PLL which makes it difficult to detect voltage sag and thereby causes maloperation of DVR. Thus filtering technique is required. In this paper CDSC based prefilter is used to eliminate these ripples which is discussed detailed in [1].

The rest of the paper is organized as follows: section-II gives description of the TDVR system and design of UDE control law. Section-III presents the simulation results of UDE based TDVR mitigating the voltage disturbances and further results pertaining to parameter mismatch conditions are also portrayed. Finally, conclusions are given in Section-IV.

II. Design of UDE Control

A. Description of TDVR system

The equivalent circuit of TDVR is shown in Fig.2. The state variables in this circuit are current through the filter inductor and the voltage across the series capacitor. The dynamics of this system are given by the following differential equations:

$$\begin{aligned} V_{inv} &= L_f \frac{di_f}{dt} + R_f i_f - V_{se} \\ i_s &= -C_{se} \frac{dV_{se}}{dt} - i_f \end{aligned} \quad (1)$$

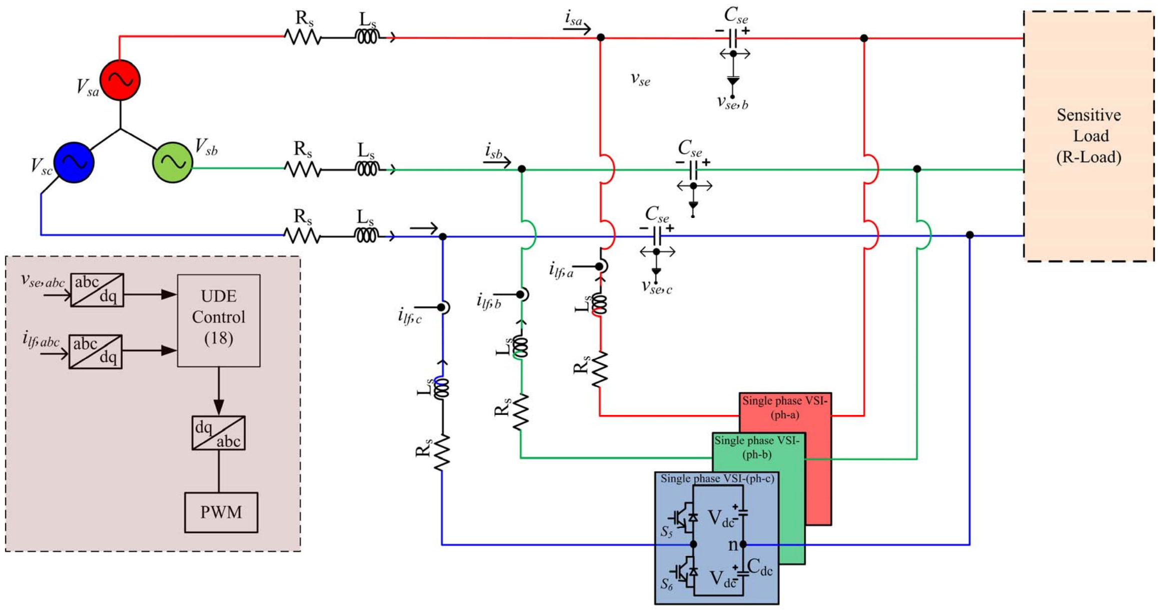

Fig.1 Block diagram of three phase TDVR system

where the description of parameters in (1) are provided in the appendix

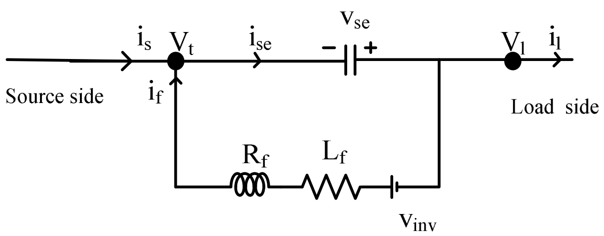

Fig.2 Equivalent circuit of TDVR in distribution system

Before developing the proposed UDE-based voltage control scheme, the differential equations governing the equivalent circuit by considering filter parameter uncertainties and load disturbances is derived first. By substituting the nominal values for the parameters in (1) it can be rewritten as follows:

$$\frac{di_f}{dt} = -\frac{R_{f0}}{L_{f0}} i_f + \frac{1}{L_{f0}} v_{se} + \frac{1}{L_{f0}} v_{inv} + f_{i_f}(t) + D_{i_f}(t)$$
$$\frac{dV_{se}}{dt} = -\frac{1}{C_{se0}} i_s - \frac{1}{C_{se0}} i_f + f_{v_{se}}(t) + D_{v_{se}}(t) \tag{2}$$

where f_{if} and f_{Vse} represent uncertain dynamics caused by the parameter variations, and $D_{if}(t)$ and $D_{Vse}(t)$ are unknown external(load) disturbances respectively. Here uncertainties in filter parameter variations are considered for deriving control equation. Uncertain dynamics in (2) are expressed as

$$f_{i_f}(t) = -\frac{\Delta R_f}{L_{f0}} i_f - \frac{\Delta L_f}{L_{fo}} \frac{di_f}{dt} \text{ and } f_{V_{se}}(t) = -\frac{\Delta C_{se}}{C_{se0}} \frac{dv_{se}}{dt}$$

where $\Delta R_f = R_f - R_{f0}$; $\Delta L_f = L_f - L_{f0}$;

$\Delta C_{se} = C_{se} - C_{se0}$; and "0" denotes nominal parameter value.

B. UDE Law

Let $x = [i_f, v_{se}]^T$ is the state vector, $u=[v_{inv}, i_s]^T$ is the control input vector, $f=[f_{if}, f_{Vse}]^T$ is the unknown dynamics vector and $d_0=[0,d_0]$, $d=[0,d]^T$ is the known and unknown load disturbance vector. The mathematical model of (2) can be expressed in state space format as shown below

$$\dot{x}(t) = Ax(t) + Bu(t) + f(t) + d(t) + d_0(t) \tag{3}$$

where A is the state matrix and B is the control matrix (A and B matrix is given in appendix) Now a reference model is designed which satisfies the desired specification and is given as

$$\dot{x}_r(t) = A_r x_r(t) + B_r c(t) \tag{4}$$

where $x_r = [i_{fr}, V_{ser}]^T$ is the reference state vector, $c = [i_f^*, V_{se}^*]^T$ is the reference command vector. A_r and B_r are constant matrices (the values are given in appendix). Let e be the state error between the reference model and actual system and is given as

$$e(t) = x_r(t) - x(t) \tag{5}$$

Now a control input vector should be determined such that the $x(t)$ in (5) should asymptotically tracks its reference trajectory $x_r(t)$. Thus from (3) $u(t)$ can be determined and is given as

$$u(t) = B^{-1}[A_r x(t) + B_r c(t) - Ax(t) - f(t) - d(t) - d_0(t)] \tag{6}$$

The asymptotic tracking for the above defined control input vector is verified as follows

substitute (7) into (3) then the resultant is given as

$$\dot{x}(t) = Ax(t) + B\left\{B^{-1}\left[\begin{matrix} A_r x(t) + B_r c(t) - Ax(t) - \\ f(t) - d(t) - d_0(t) \end{matrix}\right]\right\} + f(t) + d(t) + d_0(t)$$

$$\dot{x}(t) = A_r x(t) + B_r c(t) \tag{7}$$

by subtracting (7) from (4) gives

$$\dot{x}_r(t) - \dot{x}(t) = A_r(x_r(t) - x(t))$$

$$\dot{e}(t) = A_r e(t) \tag{8}$$

The Eigen values of A_m are negative and thus ensuring the condition of asymptotic stability i.e., the error dynamics in (8) converges to zero. The above equation (7) is valid if B is invertible and further the equation cannot be used directly because it consists of unknown dynamics and external disturbances. From (3) the disturbance and uncertainties vector can be defined as

$$u_d(t) = f(t) + d(t) \tag{9}$$

Thus following the design procedures presented in [9], if a filter $g_f(t)$ is chosen appropriately, $u_d(t)$ (control signal consists of unknown dynamics) can be approximated by

$$\hat{u}_d(t) = u_d(t) * g_f(t) \tag{10}$$

where "*" is a convolution operator and a control vector, $u_d(t)$ can be expressed as

$$u_d(t) = \dot{x}(t) - [Ax(t) + Bu(t) + d_0(t)] \tag{11}$$

by combining the (6) , (9) and (10) control signal results to (12)

$$u(t) = B^{-1}[A_r x(t) + B_r c(t) - Ax(t) - u_d(t) * g_f(t)] \tag{12}$$

substituting (12) into (11) results in

$$u(t) = B^{-1}[A_r x(t) + B_r c(t) - Ax(t) - d_0(t) - [\dot{x}(t) - Ax(t) - Bu(t) - d_0(t)] * g_f(t)] \tag{13}$$

and the UDE based control law can be derived as

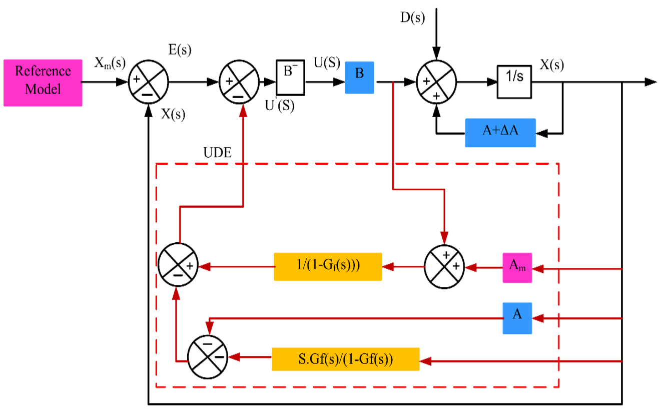

Fig.3 Structural diagram of UDE control law

$$u(t) = B^{-1}\left[\ell^{-1}\left\{\frac{1}{1-G_f(s)}\right\} * (A_r x(t) + B_r c(t)) - Ax(t) - d_0(t) - \ell^{-1}\left\{\frac{sG_f(s)}{1-G_f(s)}\right\} * x(t)\right] \tag{14}$$

where $\ell^{-1}$is the inverse Laplace transform operator. Strictly, filter $G_f(s)$ must be designed as a proper stable filter with unity gain and zero phase shift over the spectrum of the lumped disturbances $u_{de}(t)$ and zero gain elsewhere. However, it is hard to fully meet this demand. Here, a first-order low-pass filter is chosen because it is simple enough and can cover the spectrum of the major uncertainty and disturbance by setting an appropriate bandwidth [12], i.e.,

$$G_f(s) = \frac{\beta}{s+\beta} \tag{15}$$

where β is the bandwidth of $G_f(s)$. It is also worth noting that

$$\frac{1}{1-G_f(s)} = 1 + \frac{\beta}{s} \tag{16}$$

and

$$\frac{sG_f(s)}{1-G_f(s)} = \beta \tag{17}$$

Considering (16) and (17), the UDE based control law (14) can be rearranged in the s-domain form as shown below.

$$U(s) = B^{-1}\left[\begin{array}{l}(A_r X_r(s) + B_r C(s)) - (AX(s) + D_0(s)) \\ + (\beta I - A_r)E(s) - \frac{\beta}{s} A_r E(s)\end{array}\right] \tag{18}$$

Fig.3 shows the structural representation of UDE control scheme. The (16) consists of: (i) differential feedforward term, (ii) model inversion to cancel known model dynamics and (iii) PI regulator to compensate the tacking error between the reference state vector and the actual state vector.

III. Simulation Results

The dynamic performance of TDVR to compensate voltage sags with the proposed control scheme is tested in MATLAB software. The source voltage of 230 V(rms) is considered as 1 pu. Further the efficacy of the proposed control scheme for parameter mismatch is also validated and respective results are presented.

A. Performance of TDVR under symmetric and asymmetric voltage sags

Fig. 4 shows the results of voltage sag compensation by TDVR. Firstly, up to 0.08 sec the source voltage as shown in Fig.4(a) is in its nominal condition and therefore the injected voltage is zero. From 0.08 s to 0.17 s a symmetric voltage sag of 0.3 pu occurs in the source voltage. During this time interval, the TDVR injects the required voltage (as shown in Fig.4(b)) to maintain the load voltage at prefault level shown in Fig.4(c). From 0.2 sec to 0.28 sec, the source voltage undergoes single phase voltage sag as shown in Fig.4(d). The TDVR produces the necessary voltage (Fig.4(e)) to increase the load voltage to the prefault value which can be observed from Fig.4(f). Similarly, Fig.4(g)-(i) depicts the two-phase sag scenario in phase-b and phase-c and it is observed that load voltage is maintained constant. Thus the waveforms confirm that the UDE based control of

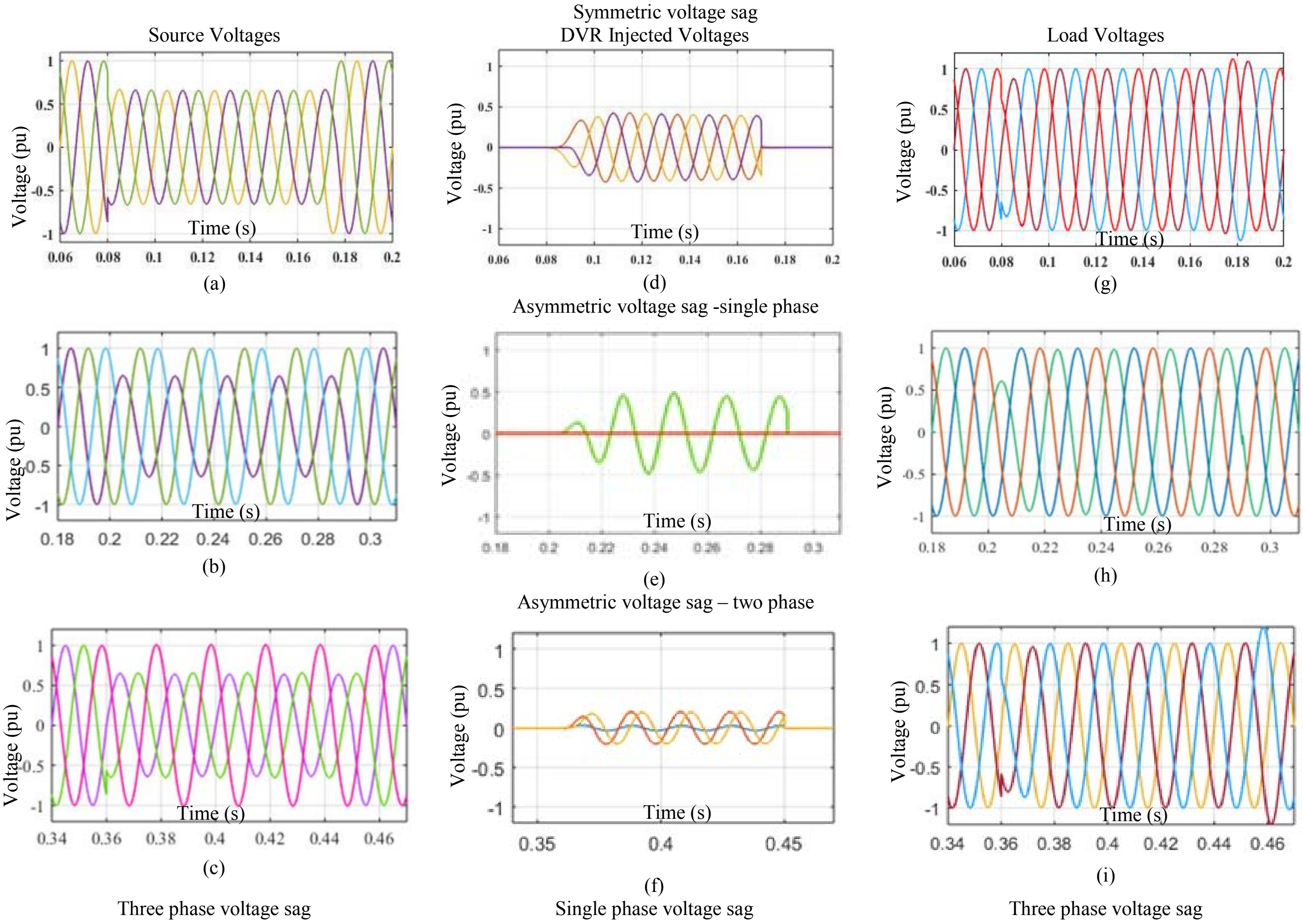

Fig.4 Performance of UDE based control for TDVR under symmetric and asymmetric sag

Performance of UDE control under three phase sag with LC variation

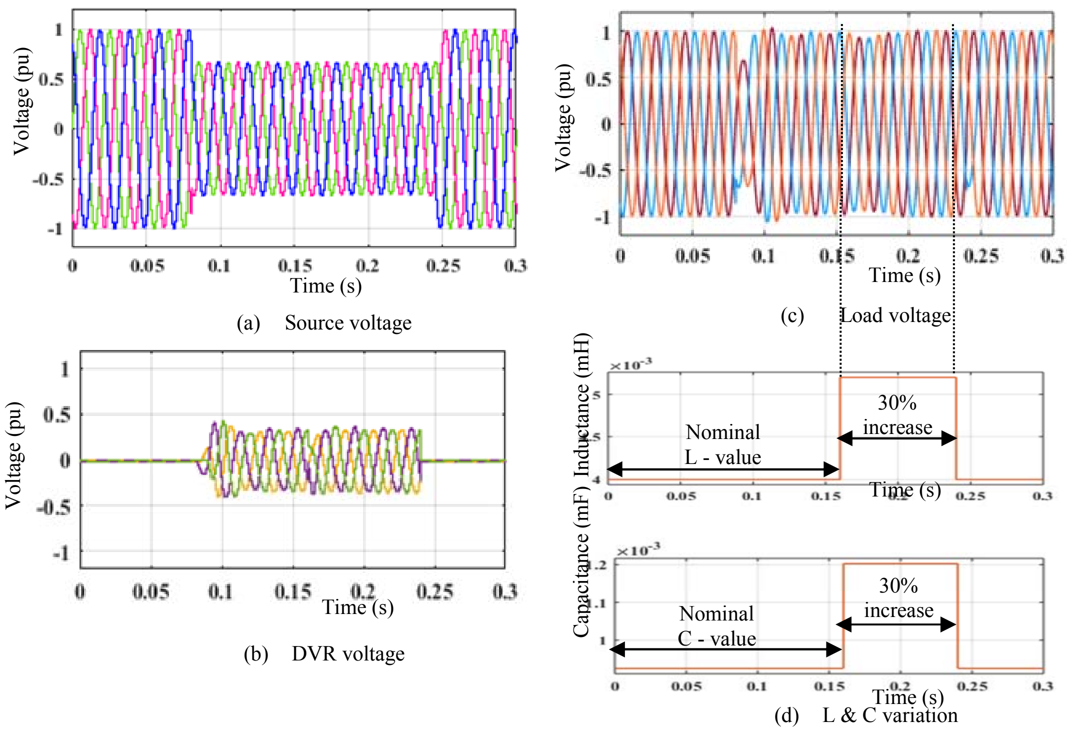

Fig.5 Dynamic performance of UDE based control for TDVR tested for Symmetric sag with LC variation

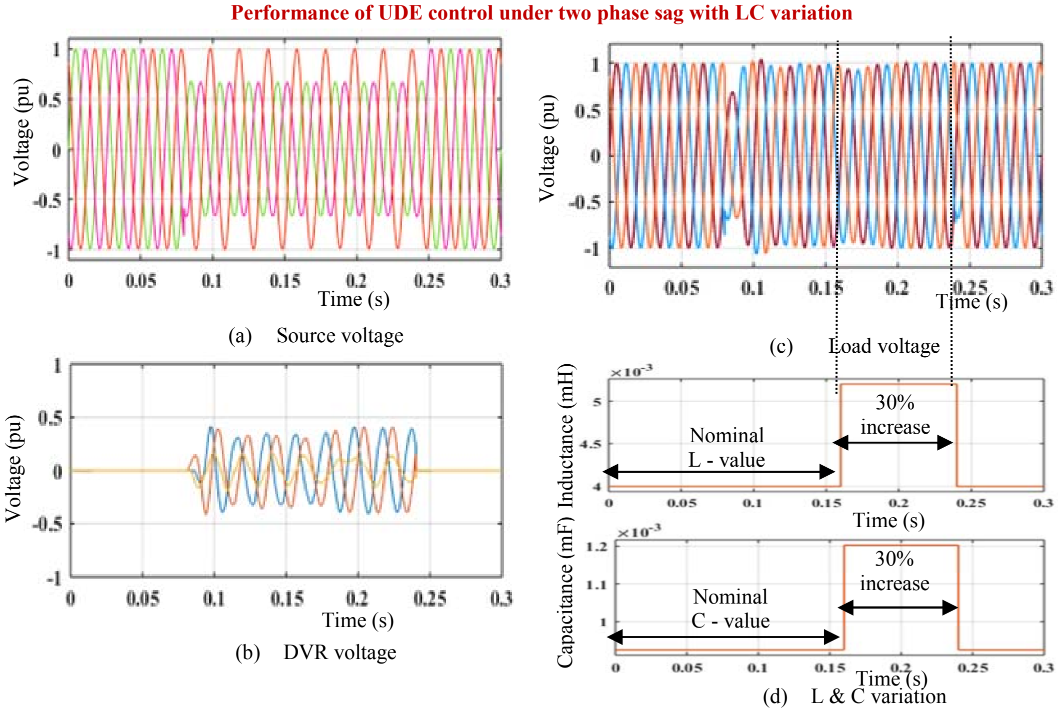

Fig.6 Dynamic performance of UDE based for TDVR tested for two phase sag (asymmetric) with LC variation

TDVR works effectively for symmetric and asymmetric voltage sags.

B. Performance of TDVR under parameter mismatch conditions

In the previous section the simulation results for compensation of voltage sags by TDVR based on UDE control law are presented. To prove the robustness of the proposed control, scheme the dynamic performance of TDVR compensating symmetric and asymmetric voltage sags under mismatch conditions of TDVR filter parameters is analysed. The main causes for variation of filter parameters are due to tolerance of filter components (ageing effect), operating conditions. Thus it is necessary to design the controller which is robust to parameter variation. The filter parameters are varied to 30% (increase) from its nominal value (L:4 mH to 5.2 mH and C:925µF to 1020µF). Fig.5 shows the performance of proposed UDE control scheme under the filter parameter mismatch conditions. Initially the filter parameters are maintained at nominal values. The symmetric voltage sag is initiated at 0.08 s with nominal L and C values and the parameter variation i.e., step change in the filter parameters (both L and C as shown in Fig.5(d)) is done at 0.16 s and continued up-to 0.24 s where the voltage sag duration is completed. During this time, it is observed that the load voltage as seen in the Fig.5© shows that though the parameters are varied the load voltage is maintained at constant value.

Fig.6 depicts the dynamic performance of UDE based TDVR for asymmetric sag under parameter mismatch condition. Similar to the above case L and C are increased to 30% from nominal value. It can be seen that TDVR maintains the constant load voltage and precisely the focusing point is the effectiveness of the UDE control scheme compensating the asymmetric voltage under parameter mismatch conditions.

The above simulation studies prove the robustness of UDE control law for the parameter mismatch conditions and voltage disturbances (voltage sags).

IV. CONCLUSIONS

In this paper UDE based control for TDVR is proposed. The UDE control is employed to maintain the robustness during the filter parameter variations along with other voltage disturbances (viz., voltage sags). The control structure consists of three major parts: differential feedforward, model inversion and PI regulator. The control equation is formed using the dynamic equations of inverter along with filter which involves voltage across the filter capacitor and current through filter inductor. The main feature of proposed UDE control is assuring the robustness through estimating the uncertainties and disturbances by a suitable filter (loop filter involved in the derived UDE control law)**.** Further the proposed control has good abilities of reference tracking. Based on the simulation studies the proposed UDE based TDVR maintains load voltage at desired value for voltage disturbances along with the filter parameter mismatch conditions (30% variation in both L & C of the inverter).

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APPENDIX

v_{inv} = Inverter output Voltage;

i_s = Source Current;

i_f = Inductor Current;

v_{se} = Series Capacitor Voltage;

R_f= Filter Resistance;

L_f = Filter Inductance;

C_{se} = Series Capacitance;

$$A = \begin{bmatrix} -\frac{R_f}{L_f} & \frac{1}{L_f} \\ -\frac{1}{C_{se}} & 0 \end{bmatrix}; \; B = \begin{bmatrix} \frac{1}{L_f} & 0 \\ 0 & -\frac{1}{C_{se}} \end{bmatrix};$$

$$A_r = \begin{bmatrix} -\alpha & 0 \\ 0 & -\alpha \end{bmatrix}; B_r = \begin{bmatrix} \alpha & 0 \\ 0 & \alpha \end{bmatrix};$$

REFERENCES

[1] A. Karthikeyan, D.G.Abhilash Krishhna, Sushant Kumar, B.Venkatesa Perumal,S. Mishra, "Dual Role CDSC based Dual Vector Control for E ective Operationof DVR with Harmonic Mitigation," in IEEE Transactions on Industrial Electronics., 2018(Early Acess).

[2] J. G. Nielsen and F. Blaabjerg, "A detailed comparison of system topologies for dynamic voltage restorers," in IEEE Transactions on Industry Applications, vol. 41, no. 5, pp. 1272 - 1280, Sept.-Oct. 2005.

[3] N. H. Woodley, L. Morgan, and A. Sundaram, “Experience with an inverter-based dynamic voltage restorer,” IEEE Trans. Power Delivery, vol. 14, no. 3, pp. 1181–1186, Jul. 1999.

[4] F. Badrkhani Ajaei, S. Afsharnia, A. Kahrobaeian, and S. Farhangi, “A fast and effective control scheme for the dynamic voltage restorer,” IEEE Trans. Power Del., vol. 26, no. 4, pp. 2398–2406, Oct. 2011.

[5] W. Santos et al., "The transformerless single-phase universal active power filter for harmonic and reactive power compensation ", *in IEEE Trans. Power Electron,* vol.29, No. 7, pp. 3563-3572, 2014.

[6] B. H. Li, S. Choi, and D. Vilathgamuwa, “Transformerless dynamic voltage restorer", Proc. Inst. Elect. Elec. Gen. Transmiss. Distrib, vol.149, No. 3, pp.263-273, 2002.

[7] C. Kumar and M. K. Mishra, “Predictive voltage control of transformerless dynamic voltage restorer", *in* IEEE Transactions on Industrial Electronics, vol. 62, No. 5, pp. 2693-2697, 2015.

[8] H. Komurcugil and S. Biricik, “Time-Varying and Constant Switching Frequency Based Sliding-Mode Control Methods for Transformerless DVR Employing Half-Bridge VSI", *in IEEE Transactions on Industrial Electronics,* vol. 64, No. 4, pp. 2570-2579, 2016.

[9] Q.-C. Zhong and D. Rees, “Control of uncertain LTI systems based on an uncertainty and disturbance estimator", ASME J. Dyn. Syst. Meas. Control, Vol.126, pp. 905-910, 2004.

[10] K. Youcef-Toumi and O. Ito, “A time delay controller for systems with unknown dynamics", ASME J. Dyn. Syst. Meas. Control, Vol. 112, No. 1, pp. 133-142, 1990.

[11] J. Ren, Y. Ye, G. Xu, Q. Zhao and M. Zhu, “Uncertainty-and-Disturbance- Estimator-Based Current Control Scheme for PMSM Drives with a Simple Parameter Tuning Algorithm", *in IEEE Transactions on Power Electronics*, vol. 32, No. 7, pp. 5712-5722, 2017.

[12] Q.-C. Zhong, A. Kuperman, and R. K. Stobart, “Design of UDE-based controllers from their two-degree-of-freedom nature,” Int. J. Robust Nonlinear Control, vol. 21, no. 17, pp. 1994–2008, 2011.