Isolated H-bridge DC–DC converter integrated transformerless DVR for power quality improvement

Murat Mustafa Savrun1, Tahsin Köroğlu2, Adnan Tan3, Mehmet Uğraş Cuma4, Kamil Çağatay Bayindir5, Mehmet Tümay3

1Department of Electrical and Electronics Engineering, Adana Alparslan Türkiye Science and Technology University, Adana, Turkey
2Department of Automotive Engineering, Adana Alparslan Türkiye Science and Technology University, Adana, Turkey
3Department of Electrical and Electronics Engineering, Çukurova University, Adana, Turkey
4Department of Electrical and Electronics Engineering, Yıldırım Beyazıt University, Ankara, Turkey
5Department of Electrical and Electronics Engineering, Çukurova University, Adana, Turkey

E-mail: msavrun@atu.edu.tr

Abstract: This study presents a new H-bridge DC-DC converter-based transformerless dynamic voltage restorer topology (DVR). The proposed system can compensate balanced and unbalanced voltage sag/swell that are the most common electrical power quality problems and various harmonics. Three-wire, 380 V, 10 kVA prototype.

Widespread use of power electronics equipment causes various adverse effects in the grid and raises the phenomenon of electrical distribution systems. Sensitive loads such as communication devices, adjustable speed drives, manufacturing, and load harmonics. Therefore, to eliminate the injection transformers and by employing shunt converter to eliminate the requirement of an energy storage unit. The system is composed of H-bridge DC–DC converter equipped with a HFT with one primary and three secondary windings, is used to provide the bidirectional power flow control of DC–DC converter, whereas in-phase compensation method with the configuration of three-phase inverter and separated DC–DC-link voltage from exceeding its safe operational range in voltage swell events. Therefore, this paper focused on swell compensation and unidirectional power flow is performed. In [11], a transformerless LV DVR is realised by employing half-bridge VSC.

Recently, line transformers used for voltage matching and galvanic isolation in grid-connected topologies are eliminated by using DC–DC converter equipped with high-frequency transformer (HFT). Several studies have been performed on this issue in the literature. The related topology is used in the applications of smart transformers, grid-connected photovoltaic (PV) systems, PV/battery hybrid systems etc. [12–15]. To eliminate the injection transformer and energy storage unit from the system, DVR topologies that are characterised by three-phase rectifier, HFT and unidirectional isolated DC–DC converter have been developed in [16, 17]. HFT provides the isolation of the system rather than a bulky line transformer. The usage of the three-phase rectifier enables to eliminate the costly battery requirement. The DC–DC converters of the systems are formed with a topology that provides unidirectional power flow.

The cycloconverter-based DC–DC converter topology, which is relatively complex, enables transformerless DVR topology [18–21]. Multilevel inverter topologies operated at medium-voltage level allow transformerless connection with modularised circuit layout of the cascade inverter topology [22–25].

As it is understood from the literature review, it is aimed to both improve the performance and reduce the cost of the DVR. Table 1 shows the benchmarking of the DVR topologies available in the literature.

This paper proposes a new isolated H-bridge DC-DC converter-based DVR topology to compensate the voltage sag/swell. In the proposed topology, small-sized and low-cost HFT, that is designed to have one primary/three secondary windings, is used to provide galvanic isolation instead of bulky and costly line transformers.
Costly energy storage devices are eliminated from the DVR topology by a full-bridge diode rectifier connected in parallel to the load side. Single-phase shift (SPS) modulation method is used for bidirectional power transfer in the H-bridge DC–DC converter and is applied to each series converter to control them independently. The performance of the proposed system is verified with an experimental prototype. The remaining of this paper is organised in the following manner: the power circuit topology of the proposed system is described in Section 2. The control schemes of the DVR and DC–DC converter are presented in Section 3. The design details of the experimental prototype and the experimental results are presented in Section 4. Finally, Section 5 analyses the results and contributions of this paper.

2 Proposed H-bridge DC–DC converter-based transformerless DVR configuration

The power circuit configuration of the proposed system is illustrated in Fig. 1 consists of shunt converter, isolated H-bridge DC–DC converter, three single-phase H-bridge inverters and LC filters. The shunt converter, which is connected to the load side, composed of a three-phase converter and has a constant DC-link voltage, is used to eliminate the need for costly energy storage units. The H-bridge-based bidirectional DC–DC converter allows the DVR to compensate both voltage sag and voltage swell with the capability of bidirectional power flow. Use of isolated H-bridge DC–DC converter in DVR also makes it possible to eliminate the bulky line transformer in the point of common coupling (PCC). As shown in Fig. 1, the HFT is designed with one primary/three secondary windings. Thus, the isolation between the series converters in each phase is ensured by DC links. The usage of dual active bridge (DAB) topology makes it possible to use zero-voltage switching operation and phase shift operation to improve the performance of the system [26–30]. The output of the isolated H-bridge converter is composed of three DC-link capacitors that supply the required power for compensation of the sensitive load. LC filter is used at the output of the VSC to filter the oscillations.

3 Control scheme of the system

The controller of the proposed system consists of two parts: a DVR controller and DC–DC converter controller. The controller of DVR shown in Fig. 2 is designed to compensate the voltage sag/swell and to control each phase independently. The controller of the DVR monitors the voltages at the PCC for the detection of the missing/excessive voltage. The control process starts with the measurement of bus voltages. To detect the balanced and unbalanced voltage sag/swell, a hybrid method, which is developed by Koroglu et al. [31], consisting of improved Clarke transformation and enhanced phase-locked loop (EPLL) is
The method of EPLL described in [32] is used to calculate the magnitude and the phase of the phase voltages for synchronisation. The improved Clarke transform is adopted to calculate the magnitudes of phase voltages. The two phases (α, β) of stationary reference frame are computed by using virtual phase voltages derived by using the reference phase of Vph,A (voltage of phase A) according to (5) [34]. The depth of the voltage disturbance is calculated according to (6) [35].

The transformation of three-phase stationary frames (A, B, C) to two-phase stationary frame (α, β, 0) is performed by using (4). The magnitudes of phase voltages are calculated by using alpha and beta components of phases according to (5) [34]. The depth of the voltage disturbance is calculated according to (6)

\[ \begin{align*}
V_{\text{ref}} & = V_{\text{ph}} \\
V_{\text{ref_A}} & = \frac{1}{2} V_{\text{ph}} \\
V_{\text{ref_B}} & = \frac{\sqrt{3}}{2} V_{\text{ph}} \\
V_{\text{ref_C}} & = \frac{1}{2} V_{\text{ph}}
\end{align*} \]

where \( A_{\text{Clarke,n}} \) are the magnitudes of the phase voltages that are calculated by the improved Clarke transform and \( A_{\text{EPLL,n}} \) are the magnitudes of the phase voltages that are calculated by EPLL.

The reference voltage of the distorted phase is derived from the voltage at PCC by using the in-phase compensation method [35]. The aforementioned method controls the phase voltages continuously and calculates the magnitude of injection voltage according to the pre-sag and sag magnitudes and phase angles.

The switching signals of the insulated-gate bipolar transistors (IGBTs) are generated by using the carrier-based pulse-width modulation technique. The reference voltage \( V_{\text{ref}} \) is to be injected to the distribution system compared with a fixed frequency triangular carrier signal. The switching frequency of the series converters is selected as 10 kHz.

In the controller of the DC–DC converter, SPS modulation method is performed to provide the bidirectional power flow and voltage control at both sides. To be able to compensate for the balanced and unbalanced voltage sag/swell, each H-bridge converter on the secondary side is independently controlled. Therefore, independent phase shift angles are computed for each phase. The switching pairs of H bridges have a constant duty cycle (50%) and have 180° phase shift between two legs to provide the square wave AC voltage across transformer terminals. The bidirectional power flow between the DC links is provided by their own phase shift angles \( \phi_{1,2,3} \), as follows [36]:

\[ P_{D_{1,2,3}} = \frac{V_{DC} V_{DVR,DC_{-1,2,3}}}{\pi} \sin \left( \phi_{1,2,3} \right) \]

The objectives of the proposed system are (1) to compensate balanced three-phase 50% voltage sag for three periods and (2) to compensate 15%, three-phase voltage swell for three periods. The

\[ \phi_{1,2,3} = \frac{\pi}{2} \left( \frac{2}{3} \right) \]
DC-link capacitor values are calculated according to the value of power to be transferred during the voltage sag and voltage swell. When the power demand of the load group is around 15 kVA, 4.5 kVA power transfer is needed to compensate 50% three-phase voltage sag for three cycles. This means that 1.5 kVA power transfer is needed for each phase. The DC-link capacitors are calculated according to the equations below:

\[ E_{dc} = \frac{1}{2} C_{dc} (V_{dc1}^2 - V_{dcf}^2) \]  
\[ E_{dc} = tS \]  
\[ C_{dc} = \frac{2tS}{V_{dc1}^2 - V_{dcf}^2} \]

\( E_{dc} \) is the energy transferred to the DC link during the voltage sag/swell; \( S \) is transferred power; \( t \) is the duration of the disturbance; \( V_{dc1} \) is the initial capacitor voltage; and \( V_{dcf} \) is the final capacitor voltage. The DVR DC-link capacitors are determined as 20 mF for each series converter by theoretical calculations \( (V_{DVR,DC,1−2−3}) \).

In the proposed system, the LC-type inverter-side output filter equipped with passive damping method is used to attenuate the voltage harmonics and high-frequency fluctuations. Although the switching frequency harmonics can be eliminated more effectively in LCL and LLCL filters, additional voltage disturbances occur due to the load current passing through the inductance that is on the load side after the filter capacitor. So, the waveform of the load voltage is distorted. Therefore, in the proposed DVR topology, LC-type filter is preferred. The parameters of the filter are summarised in Table 3.

The isolated H-bridge DC–DC converter is used to regulate the DC-link voltages of the DVR during the voltage sag/swell and provide isolation of the system with HFT. The HFT takes the part of bulky injection transformers in the traditional DVR topology. Thus, the transformer with a volume of 1386 cm\(^3\) (16.5\times12\times7) is employed rather than the transformer with a volume of 35,280 cm\(^3\) (35\times16\times21\times3 ph) as illustrated in Fig. 6. Thus, a significant reduction in DVR size is achieved with the proposed topology. Furthermore, this paper has the potential to reduce costs because of the high costs of energy storage units and bulky injection transformers as well as the downward trend in the costs of semiconductors.

### Table 2 Parameters of the load group

| Load parameters | 7 kVAR with two steps |
|-----------------|--------------------|
| Inductive loads | step 1: 5 kVAR |
|                 | step 2: 2 kVAR |
| Resistive loads | 13.5 kW with three steps |
|                 | step 1: 3\times2 kW |
|                 | step 2: 3\times1.5 kW |
|                 | step 3: 3\times1 kW |

### Table 3 Inverter output filter parameters

| Parameter               | Value |
|-------------------------|-------|
| Switching frequency     | 10 kHz |
| Resonance frequency     | 2.2 kHz |
| Passive elements        |       |
| \( L_{A,B,C} \)         | \( 0.2 \times 10^{-3} \) H |
| \( C_{IA,B,C} \)        | \( 150 \times 10^{-6} \) F |
| \( R_{da,b,c} \)        | 0.7 Ω |

20 mF for each series converter by theoretical calculations \( (V_{DVR,DC,1−2−3}) \).

The isolated H-bridge DC–DC converter is used to regulate the DC-link voltages of the DVR during the voltage sag/swell and provide isolation of the system with HFT. The HFT takes the part of bulky injection transformers in the traditional DVR topology. Thus, the transformer with a volume of 1386 cm\(^3\) (16.5\times12\times7) is employed rather than the transformer with a volume of 35,280 cm\(^3\) (35\times16\times21\times3 ph) as illustrated in Fig. 6. Thus, a significant reduction in DVR size is achieved with the proposed topology. Furthermore, this paper has the potential to reduce costs because of the high costs of energy storage units and bulky injection transformers as well as the downward trend in the costs of semiconductors.
The primary-side DC link of the DC–DC converter is fed by a full-bridge diode rectifier connected in parallel to the load side. The primary-side DC-link voltage is kept constant at its steady-state value (∼530 V) under normal condition by the three-phase converter (active rectifier). The secondary-side DC-link voltages remain constant at 160 V to perform successful compensation performance. The parameters of the developed system are shown in Table 4.

The presented system is tested under two case studies summarised in Table 5. Case 1 has been formed by considering the worst operating condition for the proposed system. Case 2 consists of both voltage sag and voltage swell.

During cases, three-phase source and three-phase load voltage measurements have been taken with Fluke 1760 PQ recorder. The three-phase source currents and single-phase (A phase) measurements have been captured with Hioki 1396 power quality analyser. The DC-link measurements have been taken with Tektronix MSO3034 oscilloscope. All measurements have been captured simultaneously.

**Case 1:** In this case, the effect of three-phase balanced 50% voltage sag for five periods is examined under a load combination of 13.5 kW resistive and 7 kVAR inductive. The voltage magnitude of phase A of the supply sags from 217 to 113 V RMS. The missing voltage should be detected and injected to the system to protect the load from disturbance as soon as possible. Fig. 7 shows the compensation performance of the proposed system.

As can be seen from this figure, the proposed system achieves the voltage sag compensation with a fast initial response for the specified case study. The compensation of the sagged phase to nominal value lasts less than a half cycle.

As illustrated in Fig. 7, when phase voltages sag, DC-link voltages of the DVR and shunt converter are kept under the desired voltage limits via bidirectional H-bridge DC–DC converter controller and shunt converter. The PI controllers of the DC–DC converter increase the phase shift angles of the related bridges according to the error value of the DC link. Thus, the DC-link voltages are held at a certain level.

The root-mean-square (RMS) trends of the supply, load and injected voltages are shown in Fig. 7. The RMS of supply voltage can vary due to other loads operating simultaneously such as air conditioners, lamps etc. The sag detection and reference extraction times cause instantaneous voltage fluctuations at point of voltage sag start and end. Total harmonic distortion (THD) of load voltage in phase A is about 2.8% and is always kept below voltage harmonic limits of the IEEE 519-1992 standard [38].

**Case 2:** In this case, the effect of unbalanced voltage disturbance for five periods is investigated under the same load combination. The voltage magnitudes of phase A and C sag from 217 V RMS to 133 V, while the voltage magnitude of phase B reached 20% of its nominal value (263 V RMS). As illustrated in Fig. 7 test results for case 1
Fig. 8, the missing and excessive voltages are detected in less than a half cycle and compensated by the proposed system.

As illustrated in Fig. 8, the DC-link voltages of the DVR and shunt converter maintain within specified voltage limits during disturbance, thanks to bidirectional power flow capability of the system. The compensation of the excessive voltage is carried out by power transfer in the direction from DVR to shunt converter-side DC link, while the compensation of the sagged voltages is carried out by power transfer in the opposite direction.

The RMS voltages of the loads are kept within the limits of the IEEE 1159-1995 standard despite the fact that the RMS voltages of the source change during the disturbance condition. The RMS trend of the source, load, and injected voltages and THD of the load voltages are presented in Fig. 8. THD of load voltages in phases is about 2.1% and is always kept below voltage harmonic limits of the IEEE 519-1992 standard [34].

The sag/swell compensation performance of the developed prototype is summarised in Table 6.

### 5 Conclusion

In this paper, an isolated H-bridge DC–DC converter-based novel transformerless DVR topology and control method have been proposed. The main advantages of the proposed topology are as follows:

- The usage of the isolated H-bridge DC–DC converter allows providing isolation in the system rather than bulky line transformers.
- Transformerless topology allows for a significant reduction in the size and cost of the overall system.
- Separate DC-link capacitors also provide isolation between the phases.
- The shunt converter, which is connected in parallel to the load side, reduces the system cost by eliminating the need for energy storage units.

The performance results of the 380 V, three-phase/three-wire, 10 kVA system are examined. Experimental results show that the proposed topology and controller have compensated the voltage sag/swell under a half cycle of the AC waveform and the voltage THD can be kept within the limits of the IEEE standards. The reliability and realisation of the system have been verified with case studies.

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References

[1] Bollen, M.H.J.: 'Understanding power quality problems: voltage sags and interruptions', IEEE Press, New York, 2001.

[2] Nielsen, J.G., Blaabjerg, F.A.: 'A detailed comparison of system topologies for dynamic voltage restorers', IEEE Trans. Ind. Appl., 2005, 41, (5), pp. 1272–1280.

[3] Jowder, F.A.L.: 'Design and analysis of dynamic voltage restorer for deep voltage sag and harmonic compensation', IET Gener. Transm. Distrib., 2009, 3, (5), pp. 547–560.

[4] Shi, J., Tang, Y., Yang, K., et al.: 'SMES based dynamic voltage restorer for voltage fluctuations compensation', IEEE Trans. Appl. Supercond., 2010, 20, (3), pp. 1360–1364.

[5] Choi, S.S., Li, J.D., Mahinda Vilathgamuwa, D.M.: 'A generalized voltage compensation strategy for mitigating the impacts of voltage sags/swells', IEEE Trans. Power Deliv., 2005, 20, (3), pp. 2289–2297.

[6] Kenneth, E.K., Choi, S.S., Mahinda Vilathgamuwa, D.: 'Analysis of series compensation and DC-link voltage controls of a transformerless self-charging dynamic voltage restorer', IEEE Trans. Power Deliv., 2004, 19, (3), pp. 1511–1518.

[7] Lu, Y., Xiao, G., Lei, B., et al.: 'A transformerless active voltage quality regulator with the parasitic boost circuit', IEEE Trans. Power Electron., 2014, 29, (4), pp. 1746–1756.

[8] Kumar, C., Mishra, M.K.: 'Predictive voltage control of transformerless dynamic voltage restorer', IEEE Trans. Ind. Electron., 2015, 62, (5), pp. 2693–2697.

[9] Zhou, M., San, V., Su, M., et al.: 'Transformer-less dynamic voltage restorer based on a three-leg ac/ac converter', IET Power Electron., 2018, 11, (13), pp. 2045–2052.

[10] Lam, C.S., Wong, M.C., Han, Y.D.: 'Voltage swell and overvoltage compensation with additional power flow controlled dynamic voltage restorer', IEEE Trans. Power Deliv., 2008, 23, (4), pp. 2513–2521.

[11] Komurcugil, H., Biricik, S.: 'Time-varying and constant switching frequency-based sliding-mode control methods for transformerless DVR employing half-bridge VSI', IEEE Trans. Ind. Electron., 2017, 64, (4), pp. 2570–2579.

[12] Sochor, P., Akagi, H.: 'Theoretical comparison in energy-balancing capability between star- and delta-configured modular multilevel cascade inverters for utility-scale photovoltaic systems', IEEE Trans. Power Electron., 2016, 31, (3), pp. 1980–1992.

[13] Fuentes, C.D., Rojas, C.A., Renadeneau, H., et al.: 'Experimental validation of a single and cascaded H-bridge multilevel inverter for multistring photovoltaic systems', IEEE Trans. Ind. Electron., 2017, 64, (2), pp. 930–934.

[14] Costa, L.F., Carne, G.D., Buticchi, G., et al.: 'The smart transformer: a solid-state transformer tailored to provide ancillary services to the distribution grid', IEEE Power Electron. Mag., 2017, 4, (2), pp. 56–67.

[15] Peña-Alzola, R., Gohil, G., Mathe, L., et al.: 'Analysis of system topologies, controls, and applications', IEEE Trans. Ind. Electron., 2009, 4, (2), pp. 724–738.

[16] Al-Haddid, H.K., Gole, A.M., Jacobson, D.A.: 'A novel configuration for a cascade inverter-based dynamic voltage restorer with reduced energy storage requirements', IEEE Trans. Power Deliv., 2008, 23, (2), pp. 881–888.

[17] Hiltunen, J., Vaisanen, V., Jutunen, R., et al.: 'Variable-frequency phase shift modulation of dual active bridge converter', IEEE Trans. Power Electron., 2015, 30, (12), pp. 7138–7148.

[18] Hosseini, S.H., Sharifian, M.B.B., Sabahi, M., et al.: 'Bi-directional power electronic transformer-based compact dynamic voltage restorer'. IEEE Power and Energy Society General Meeting, Calgary, AB, Canada, July 2009, pp. 1–5.

[19] Jimichi, T., Kaihi, J., Sabahi, M., et al.: 'Three-phase HFL-DVR with independently controlled phases', IEEE Trans. Power Electron., 2012, 27, (4), pp. 1706–1718.

[20] Goharrizi, A.Y., Hosseini, S.H., Sabahi, M., et al.: 'Three-phase HFL-DVR with independently controlled phases', IEEE Trans. Power Electron., 2012, 27, (4), pp. 1706–1718.

[21] Rodriguez, J., Lai, J.S., Peng, F.Z.: 'Multilevel inverters: a survey of topologies, controls, and applications', IEEE Trans. Ind. Electron., 2002, 49, (4), pp. 724–738.

[22] Al-Haddid, H.K., Gole, A.M., Jacobson, D.A.: 'A novel configuration for a cascade inverter-based dynamic voltage restorer', IEEE Trans. Power Deliv., 2008, 23, (2), pp. 889–896.

[23] Lam, C.S., Wong, M.C., Han, Y.D.: 'Voltage swell and overvoltage compensation with additional power flow controlled dynamic voltage restorer', IEEE Trans. Power Deliv., 2008, 23, (4), pp. 2513–2521.

[24] Li, B.H., Choi, S.S., Vilathgamuwa, D.: 'Transformerless dynamic voltage restorer', IET Gen., Proc. Transm. Distrib., 2002, 149, (3), pp. 263–273.

[25] Savrun, M.M., Tan, A., Köroğlu, T., et al.: 'A digital predictive current-mode controller for single-phase high-frequency transformer-isolated dual-active bridge dc–dc converter', IEEE Trans. Ind. Electron., 2016, 63, (9), pp. 5943–5952.

[26] Dutta, S., Hazra, S., Bhattacharya, S.: 'A digital predictive current-mode controller for single-phase high-frequency transformer-isolated dual-active bridge dc–dc converter', IEEE Trans. Ind. Electron., 2016, 31, (12), pp. 8552–8561.

[27] Karimi-Ghartermani, M., Iravani, M.R.: 'A non-linear adaptive filter for online signal analysis in power systems: applications', IEEE Trans. Power Deliv., 2002, 17, (2), pp. 617–622.

[28] Inci, M., Bayindir, K.C., Tümay, M.: 'Improved synchronous reference frame based controller method for multifunctional compensation', Elect. Power Syst. Res., 2016, 141, pp. 500–509.

[29] Areges, M., Dalfner, J., Houmann, K.: 'Three-phase four-wire shunt active filter control strategies', IEEE Trans. Power Electron., 1997, 12, (2), pp. 311–318.

[30] Nielsen, J.G., Blaabjerg, F.: 'Control strategies for dynamic voltage restorer compensating voltage sags with phase jump'. IEEE Applied Power Electronics Confer. Exposition, Anaheim, CA, USA, March 2001.

[31] Karshenas, H.R., DineshBajaj, H., Babaei, A., et al.: 'Bidirectional dc–dc converters for energy storage systems', Energy storage in the emerging era of smart grids. 2011, Chapter 8.

[32] Savrun, M.M., Tan, A., Köroğlu, T., et al.: 'DSP controlled voltage compensation and DC-link voltage controls of a transformerless self-charging dynamic voltage restorer'. IEEE Trans. Power Electron., 2012, 27, (4), pp. 1706–1718.

[33] Al-Haddid, H.K., Gole, A.M., Jacobson, D.A.: 'A novel configuration for a cascade inverter-based dynamic voltage restorer', IEEE Trans. Power Deliv., 2008, 23, (2), pp. 889–896.

[34] Li, B.H., Choi, S.S., Vilathgamuwa, D.: 'Transformerless dynamic voltage restorer', IET Gen., Proc. Transm. Distrib., 2002, 149, (3), pp. 263–273.

[35] Hiltunen, J., Vaisanen, V., Jutunen, R., et al.: 'Variable-frequency phase shift modulation of dual active bridge converter', IEEE Trans. Power Electron., 2015, 30, (12), pp. 7138–7148.

[36] Bollen, M.H.J.: 'Understanding power quality problems: voltage sags and interruptions', IEEE Press, New York, 2001.

[37] Bollen, M.H.J.: 'Understanding power quality problems: voltage sags and interruptions', IEEE Press, New York, 2001.