# Investigation on three-inverter fed two OEWIM drives

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***Abstract*—The AC drive configuration presented in this article consists of two open-end winding induction motors (OWEIM) fed by three two-level inverters for EVs. One end of both the OEWIMs are connected to the output terminals of an inverter whereas the other three-phase terminals of both the OEWIMs are connected to two other inverter outputs. This proposed configuration is capable of parallel operation where they are connected to a common shaft. This topology has several advantages such as redundant switching states, half-rated DC link capacitors and power semiconductor devices. Further this results in reduction in size of the overall size of the entire configuration. The common inverter is rated for $V_{dc}$ whereas the other two inverters are rated for $V_{dc}/2$, resulting in only three inverters for the entire drive system, while the conventional OEWIM require four inverters for the same operation. A fuzzy logic based (field-oriented control) FOC is used for the implementation of the proposed drive system. First the simulation studies were carried out using MATLAB/Simulink and the same has been verified using OP5600 (Hardware-in-Loop) HIL system.**

***Keywords—oewim, fuzzy, drive, ac drive, opal-rt, EV***

## I. Introduction

One of the most popular and environment-friendly alternatives to the internal combustion (IC) engine is the development of electric vehicles (EVs), which is rising day-by-day steadily. The two basic modes of an EV are charging mode and driving mode. EVs consist of a battery pack, inverter and traction motor for its drive-train configuration. The inverter drives the motor and power requirement is met from the battery pack. Energy can be stored in the battery pack either from the on-board charger or from the fast charging stations. Several advancements have been reported in the literature by researchers all around the world which contributes to the growth of EVs.

In EVs, either an induction motor (IM) or permanent magnet synchronous motor (PMSM) is invariably used for driving the wheels [1]–[3]. IMs have superior advantages compared to PMSM that makes it more preferable for the EV applications. The demagnetization of the permanent magnets due to temperature effect and the need for a strong magnet makes it expensive; further, the rotor position sensing sensor is required for PMSM which makes more complicated compared to an IM [4].

Heping Liu, et. al. [5] suggested that the motors employed for drive applications should have exceptional controlled-torque characteristic to satisfy frequent start/stop, speedup/slowdown, and regeneration energy feedback, increased torque at lower speed, reduced torque and constant power run at higher speed. M. Zeroulia, et.al. [6] compared and analyzed the electric-propulsion systems for a parallel hybrid electric vehicle (HEV) and presented the most suitable choice for the same, which has been accepted widely. The comparative study was drive-specific for electric-propulsion system, which included dc motor, IM, PMSM, and switched reluctance motor (SRM). The analysis suggested that squirrel-cage induction motor meets the major requirements for propelling an HEV. Further study conducted by L. Di Leonardio, et.al [7] conducted studies on type of motor for EVs show that IM is highly recommended for traction applications, which include all configurations of EVs.

Pennycott et.al [8] presented the reduction in energy savings by minimizing the power loss in the motor by with respect to wheel-torque. The loss in power during straight-line drive and inclined slope on EVs for various motors were investigated using off-simulation characteristics. Chih Ming, et.al. [9] suggested two usage of two power sources for motors as the driving range of the battery electric vehicles (BEVs) had pronounced driving range. Hence the second source can be a fuel cell or a super capacitor. The presence of two independent sources allows the use of dual inverter to feed the induction motor from both ends. Hence the stator windings are opened and each winding is fed from both ends thereby inviting the advantages of open-end winding induction motor drives [10]. In the present context, the addition of EVs may depend on transportation policy, energy re-source benefits, technological abilities, and legislative prioritization of responses to climate change. In the present scenario, there is a huge demand for the selection of type of motor for EVs. This project envisages a novel topology with open-end winding induction motor drive for EVs. The proposed drive configuration requires less-rated power supplies, low power capacitors and switches in rectifiers/inverters with high switching redundancies. Further an efficient drive system for EVs with fast, smooth, robust, and reliable control can be obtained.

## II. Proposed Configuration And Its Control

The circuit topology for open-end winding induction motor (OEWIM) drive is shown in Fig. 1. An OEWIM is formed by removing the star-point of a conventional

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induction motor resulting in six terminals. Now the six input terminals are fed by two two-level inverters. This drive has several advantages such as reduction in *DC-link* capacitors, device power ratings, rectifiers and isolation transformers. Since it was extensively researched [13]–[18], hence the detailed analysis is avoided for the sake of redundancy. This setup is now capable of three level inversion.

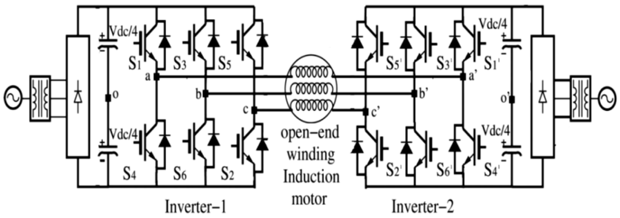

Fig. 1 Two Inverters feeding an OEWIM drive

A novel three-inverter-fed two OEWIM drive configuration is proposed for four wheel drive in EVs. The block diagram is shown in Fig. 2. In EVs there are several conditions which demand four-wheel drive operation. An OEWIM drive topology for four-wheel drive EV requires four inverters for powering them; two inverters for each OWEIM.

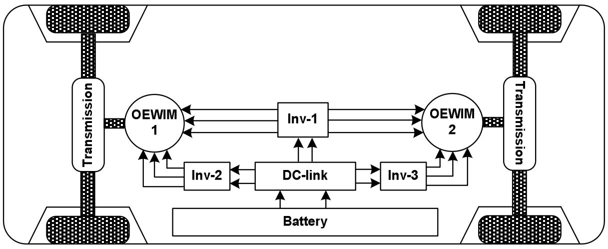

Fig. 2 Four-wheel driven EVs using triple inverters feeding two OEWIMs

This makes the entire setup bulky and costly. Hence a novel OEWIM drive topology, which requires only three inverters for feeding two OEWIM drive system is proposed as shown in Fig. 3, however, the power loss in the devices have to be accounted for owing to the fact that *Inv-1* is rated for $V_{dc}$ while, *Inv-2* & *Inv-3* are rated for $V_{dc}/2$.

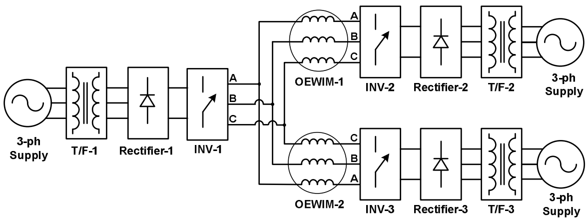

Fig. 3: Block diagram of a three isolated inverters feeding two OEWIMs

It can be observed from Fig. 2 that the three two-level three-phase inverters such as *Inv-1*, *Inv-2* & *Inv-3* are connected to a common *DC-link*. Again from the same figure, Inv-1 serves as the common inverter for *OEWIM-1* & *OEWIM-2*, while the other two ends of the two *OEWIMs* are connected to *Inv-2* & *Inv-3* respectively. The same can be visualized in circuit topology depicted in Fig. 3; however, the connection for each inverter is shown separately for the sake of clarity. Conventional single OEWIM drive requires two transformers, two rectifiers and two inverters. Additionally, in industries where conventional ac drive systems are employed, the motors are located in remote locations which require the cables to be drawn from the remote locations to the control centre. Therefore, even in the case of conventional single OEWIM, it requires six power cables which results in high initial cost as compared to the traditional three-level inverter configurations. Consequently, for the operation of two conventional OEWIMs, four isolation transformers, four rectifiers, and four inverters are required that leads to a significant increase in overall system cost, and operational cost as well. The proposed topology with two OEWIM is fed using three inverters.

Thus, three isolated power supplies are sufficient to power two OEWIMs. The *OEWIM-1* operation requires two inverters such as *Inv-1* & *Inv-2*, where if *Inv-1* is clamped to either positive rail or negative rail of the *DC-link*, while, *Inv-2* will be switched and hence, a three-level inversion is obtained. Similarly, *OEWIM-2* is connected to *Inv-1* & *Inv-3*, where *Inv-1* is clamped either to the positive rail or negative rail and Inv-3 is switched. Hence, a three-level inversion is obtained with each inverters-motor set. Thus both the OEWIMs are operated in three-level mode. The number of isolation transformers, rectifiers and inverters required for the proposed configuration is lesser compared to the conventional OEWIM drive.

Fig. 4 depicts the Field Oriented Control (FOC) method for the proposed drive configuration. The scalar control technique ("V/f" procedure) for OEWIM has its constraints as far as execution is concerned, which creates oscillations on the delivered torque. Subsequently to accomplish better powerful execution, a progressively prevalent control strategy is required for OEWIM. With the numerical handling abilities offered by the cutting edge microcontrollers, digital signal processors and FGPA; superior control technique can be actualized to decouple the generation and the magnetization functions in an OEWIM. The FOC offers improved torque response, better speed control at lower frequency and lower speed, its ability to accurately control speed dynamically, reduced motor size of the same rating compared to conventional methods, lesser cost, lowered power consumption, operation in four quadrants, and capability to randomly overload at short intervals. Further improvisation can be achieved by incorporating fuzzy logic controller in the proposed drive system. The proposed methodology uses a mathematical model to evaluate the current from the rotating reference frame of the d, q axes for the OEWIM as the proposed drive requires a robust and efficient control technique for smoother operation.

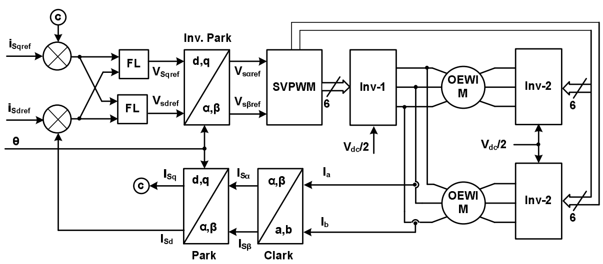

Fig. 4: FOC architecture for three inverters feeding two OEWIMs

## III. Results And Discussion

The proposed circuit topology for three inverter fed two OEWIM control was first simulated in MATLAB/Simulink environment. The obtained results were compared with the OP5600 SIL first as depicted in Fig. 5 and the same has been implemented using PHIL.

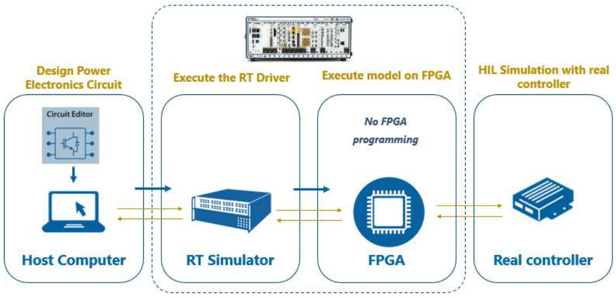


Fig. 5 Block diagram of SIL and HIL

A Power Hardware-in-Loop (PHIL) schematic of the proposed system is shown in Fig. 6. The purpose of the 200 kVA PHIL solution in the Smart Grid Laboratory is emulate power systems, devices and controls and their integration to physical model power systems, devices and controls to study system behaviour and performance for a reasonable power ranges and frequencies.

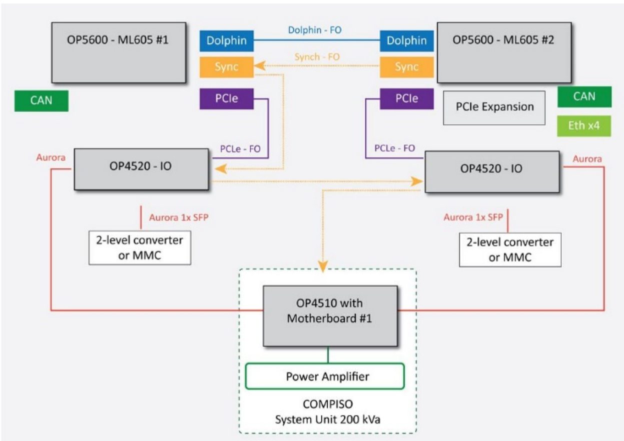


Fig. 6 200 kVA Power Hardware in the loop (PHIL) schematic

The advantage compared to the testing of use cases at very low powers and voltages, is the ability to model certain physical phenomena in a realistic way (e.g. rotating machinery thermal effects and time constants). Fig. 6 shows the Power Hardware in the Loop setup with the OPAL RT real-time simulators (OP5600), the I/O devices (OP4520) and the 200 kVA, 5kHz Egston power amplifier.

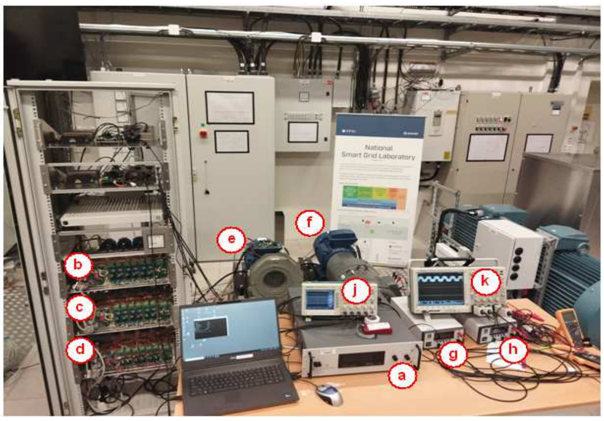


Fig. 7 Experimental setup of three three-level inverter fed two OEWIM drive; (a) 15kW programmable DC power supply, (b) Three phase two-level *Inv-1*, (c) Three phase two-level *Inv-2*, (d) Three phase two-level *Inv-3*, (e) OEWIM-1 coupled with DC generator, (f) OEWIM-1 coupled with DC generator-2, (g) Field excitation for DC generator-1, (h) Field excitation for DC generator-2, (j) DSO for visualizing the PWM signals, (k) DSO with differential voltage and current probes for measuring and capturing voltages and currents

The test setup involved building of the two level inverter, interfacing the inverter control circuit to the FPGA processor OPAL RT 5600; and connecting the inverters to the two open-end winding induction motor drives. The power supply is turned-OFF for acquiring the pictures of the test setup which is in tune with the EU electrical safety standards and all the safety precautions were adopted and followed during the hardware experimentation. Fig. 7 shows the complete setup, which included the three phase *Inv-1*, *Inv-2* and *Inv-3* in a stack; however, the OPAL RT is now shown since it remotely located whereas the connection between the OPAL RT and the inverter was established by a high speed optical fiber link. The resistive load bank is remotely located and it is connected to the DC shunt generators via high power cables running across the lab facility and it is not shown in the picture due to cumbersomeness.

Fig. 8 shows the three-level OEWIM inverter drive comprising of the motors coupled with DC generators for loading the machines.

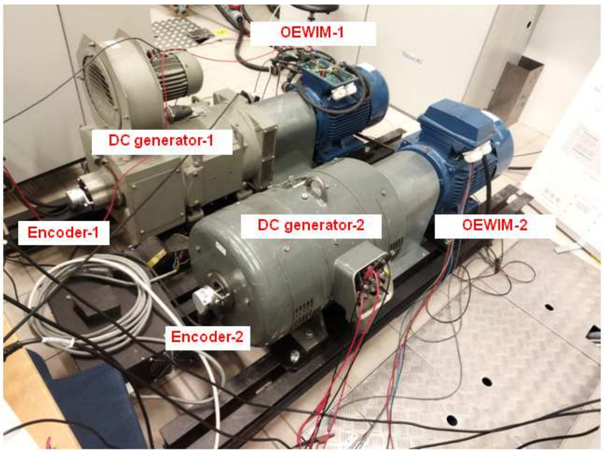


Fig. 8 Two open-end winding induction motors with coupled DC generators

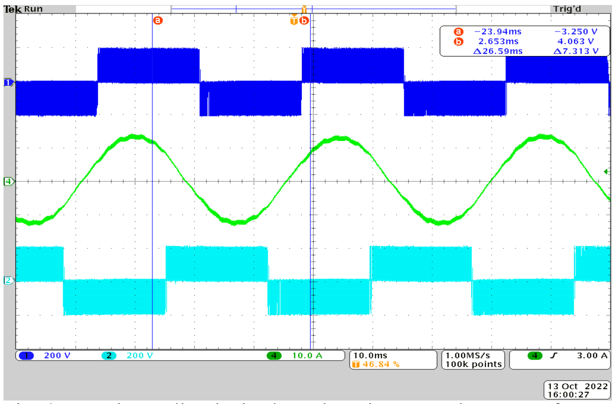


Fig. 9 Experimentally obtained results; Phase-A voltage waveforms of *Inv-1* (top trace), *Inv-2* (bottom trace); and Phase-A current waveform (middle trace)

The output waveforms for the proposed work is presented in Fig. 9, which shows the phase-A voltages of *Inv-1* (top trace), *Inv-2 (bottom trace) and motor phase-A current (middle trace).*

## IV. Conclusions And Future Scope

The performance of the proposed three inverter fed two OEWIM drives is suitable for improving the torque requirement by coupling both the motors to the same shaft. Since there are non-conformity of the voltage vectors generated by the *Inv-1* for the dual drive system, it is observed that the motor is capable of running up to 25% of the rated speed. During the execution of the project, two open-end winding induction motors were used to test the operation of this topology. The motors showed good response up to 25% of rated speed, however the set-up suffered from tripping of the inverter protection circuits above 25% of the rated speed. This is because of the inherent voltage vectors which disallows the operation during higher speeds. This is due to the fact that *Inv-1* feeds both *OEWIM-1* and *OEWIM-2*. The *Inv-1* must deliver a voltage space vector which has to be shared by *Inv-2* & *Inv-3* while *Inv-2* and *Inv-3* must generate voltage space vectors in accordance with *Inv-1* for the development of unidirectional torque. Hence the drive system suffers from serious issues such as non-conformity of the voltage vectors, torque fluctuation and uneven distribution of the stator flux. Further, for a four-wheel drive operation the speeds at which the front and back wheels rotate are different due to the nature of the terrain such as: cut-corners, uphill, downhill and curves. Additionally, during forward, reverse operation and at bends the front and back wheels in an EV is subjected to roll at different speeds (the different speeds of the left and right wheels are taken care by the differential). During these terrains conditions and operating modes there is a tendency of the wheels to slip resulting in poor steering control of the vehicle, which is not recommended in any environment.

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## REFERENCES

[1] G. Nobile, G. Scelba, M. Cacciato and G. Scarcella, "Losses minimization control for an integrated multidrives topology devoted to hybrid electric vehicles," IECON 2017 - 43rd Annual Conference of the IEEE Industrial Electronics Society, Beijing, 2017, pp. 2059-2066.

[2] Xu, Nan & Kong, & Chu, & Ju, & Jx, Yang. "Towards a Smarter Energy Management System for Hybrid Vehicles: A Comprehensive Review of Control Strategies", Applied Sciences,9. 2026. 10.3390/app9102026.

[3] Akhtar, Mohammad & Behera, Ranjan., "Optimal design of stator and rotor slot of induction motor for electric vehicle applications" in IET Electrical Systems in Transportation, 9. 10.1049/iet-est.2018.5050.

[4] Chilan, Cai & Xiao-gang, Wang & Yuewei, Bai & Yanchun, Xia & Kai, Liu., "Motor drive system design for electric vehicle", 2011 International Conference on Electric Information and Control Engineering, ICEICE 2011 - Proceedings. 10.1109/ICEICE.2011.5777955.

[5] Heping Liu, Youwei Zhou, Yu Jiang, Lin Liu, Tongbing Wang and Bo Zhong, "Induction motor drive based on vector control for electric vehicles," 2005 International Conference on Electrical Machines and Systems, Nanjing, 2005, pp. 861-865 Vol. 1.

[6] M. Zeraoulia, M. E. H. Benbouzid and D. Diallo, "Electric Motor Drive Selection Issues for HEV Propulsion Systems: A Comparative Study," in IEEE Transactions on Vehicular Technology, vol. 55, no. 6, pp. 1756-1764, Nov. 2006.

[7] L. di Leonardo, M. Popescu, G. Fabri and M. Tursini, "Performance Evaluation of an Induction Motor Drive for Traction Application," IECON 2019 - 45th Annual Conference of the IEEE Industrial Electronics Society, Lisbon, Portugal, 2019, pp. 4360-4365.

[8] A. Pennycott et. al., in "Enhancing the Energy Efficiency of Fully Electric Vehicles via the Minimization of Motor Power Losses", IEEE International Conference on Systems, Man, and Cybernetics, 2013.

[9] C. Chih Ming and Y. Kuang Shine, "System integration and power flow management for the engine-generator operation of a range-extended electric vehicle," 2013 World Electric Vehicle Symposium and Exhibition (EVS27), Barcelona, 2013, pp. 1-10.

[10] Y. Jia et al., "Control Strategy for an Open-End Winding Induction Motor Drive System for Dual-Power Electric Vehicles," in IEEE Access, vol. 8, pp. 8844-8860, 2020.

[11] M. A. Mossa and S. Bolognani, "Effective model predictive direct torque control for an induction motor drive," 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), Anacapri, 2016, pp. 746-754.

[12] H. M. Usman, H. Rehman and S. Mukhopadhyay, "Performance enhancement of electric vehicle traction system using FO-PI controller," in IET Electrical Systems in Transportation, vol. 9, no. 4, pp. 206-214, 12 2019.

[13] Srinivasan Pradabane, B.L. Narasimharaju, N.V. Srikanth, "Space-vector pulse width modulation scheme for open-end winding induction motor drive configuration", IET Power Electron., 2015, Vol. 8, Iss. 7, pp. 1083-1094.

[14] N. R. Kedika and S. Pradabane, "A Nine-Level Inverter for Open Ended Winding Induction Motor Drive with Fault-Tolerance," 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC), Nagpur, India, 2020, pp. 1-6, doi: 10.1109/STPEC49749.2020.9297732.

[15] B. D. Lemma and S. Pradabane, "Control of PMSM Drive Using Lookup Table Based Compensated Duty Ratio Optimized Direct Torque Control (DTC)," in IEEE Access, vol. 11, pp. 19863-19875, 2023, doi: 10.1109/ACCESS.2023.3249111.

[16] B. D. Lemma and S. Pradabane, "Control of Permanent-Magnet Synchronous Motors Using Fuzzy Logic Considering Parameter Variation and Diagnostic Capability For Hostile Environment Applications," 2020 IEEE First International Conference on Smart Technologies for Power, Energy and Control (STPEC), Nagpur, India, 2020, pp. 1-4, doi: 10.1109/STPEC49749.2020.9297668.

[17] S. Pradabane, "A new SVPWM for dual-inverter fed three-level induction motor drive," 2013 International Conference on Green Computing, Communication and Conservation of Energy (ICGCE), Chennai, India, 2013, pp. 514-518, doi: 10.1109/ICGCE.2013.6823491.

[18] S. Pradabane, B. L. Narasimharaju and N. V. Srikanth, "Two-quadrant clamping inverter scheme for three-level open-end winding induction motor drive," 2014 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES), Mumbai, India, 2014, pp. 1-4, doi: 10.1109/PEDES.2014.7041988.