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A Novel Method of Power Flow Control for the Compensation of Harmonics and Unbalanced Currents in Electric Railway Systems

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***Abstract*— This paper presents a novel method of power flow compensation of broad filtering and unbalance return system for electric traction systems using fuzzy logic controller. For a balanced three-phase three- wire system, the planned technique is able to control the power flow switch among the grid and the load so that the immediate compound power is maintained steady. As a result any nonlinear unbalanced load is seen by the three-phase sup- ply as a balanced linear load. The planned filter is evaluated on power substations with open delta (V-V) and Scott transformer feeders and for two-level and dual-converter in the power stage. The system has been simulated. The outcome from simulation tests shows the fuzzy logic controller advantages and the applicability compared with the direct control based algorithm in Electric railway systems**
***Keywords*— Active filters, harmonics distortion, power con- trol, rail transportation power system**

I. INTRODUCTION

ELECTRIC traction systems for passengers and cargo use various power transformer configurations, in order to feed single-phase systems from the three-phase supply. In general, three-phase to two single-phase conversion schemes use trans- formers connected in open delta (V-V), Scott or Le Blanc con- figurations [1], to improve the power system balance. However, in practical applications these transformer connections do not solve the unbalance problem seen from the three-phase side, due to the variable demands in the transport system and railroad line profile. Also, the use of uncontrolled rectification to feed the traction load contributes to the total unbalance seen from the three-phase supply. For balanced loads, this unbalance is due to the injection of current harmonics by the railroad converter to the main three-phase system, depending on the transformer connection and harmonic order [2]. Filters and unbalance compensators are therefore required to ensure proper system operation and to improve the power quality[3].

These problems are usually addressed, in practice, with the use of passive power quality compensators such as reactive power compensation capacitors and passive filters, and they are single-phase equipment installed in each feeder from the traction substation. Usually, the coupling factor between two feeders is negligible due to the independent operation of each passive compensator [4]. Moreover, passive equipment does not have the dynamic capability to adjust to changes in load, where over and under compensation happen frequently as a result of continuous changes in load conditions. There are different active power quality compensators pro- posed in the literature [5], to solve the unbalance problem, but they neglect the sequence components introduced by harmonics. Also, all of them employ two single-phase converters that have a common dc bus, but they cannot provide simultaneous compensation of unbalance and harmonic content. However, for the compensation made from the three-phase side, the use of the instantaneous active and reactive power definition [6] provides a way for simultaneous compensation of unbalance and harmonics.

The traction system under study is similar to the stage 1 railway Ezequiel Zamora in Venezuela. It draws power using a Scott transformer (115/25 kV, 60 Hz, 40 MVA). This transformer provides two single phase lines with 90 degree phase difference between them. One of the single-phase lines feeds both ways of the Charallave–Caracas section (24 km), with a ramp of 3.125%. The other single-phase line feeds both ways of the Charallave– Cua section (17.5 km), with less traffic and a ramp of 0.6%, resulting in less load for this phase. For this configuration, the Scott transformer has an unbalance in the range of 12–20% in normal operation, and 40% for emergency operation. The railway system uses eight four-wagon trains, with half of the wagons powered. Each powered wagon has four 600 kW induction machines fed with DTC controlled VSCs and single-phase PWM in the rectifier front end. The average current total demand distortion for normal operation of the system is about 20%.Only a balanced electric system without current and voltage harmonics will produce constant instantaneous power [7], as shown below in Section II-D.

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With this in mind, a compensation scheme based on direct power control (FLC) is proposed to provide simultaneous correction of harmonic content and load unbalance, commonly found in railroad systems with different transformer connection schemes in the power substation.The control strategies are simulated using a state variable model representation and experimentally validated using a DSP- based modular power electronic system able to emulate the electric traction system operating conditions, the open delta and Scott transformer connection schemes, the filtering and the load balancing power converters [8].

The power range for the railroad application in this paper is around 10 MVA, and its implementation using multilevel converters have several advantages. Multilevel converters continue to be a topic of intense research and there are several modulation techniques, reported in the literature with several ad- vantages over conventional two-level converters [9].An important advantage of multilevel converters is the possibility to improve harmonic content of the synthesized voltage with a reduced amount of commutation. Another advantage of multilevel converters is the possibility to reach higher voltage levels and higher power ratings with power devices having lower break- down voltages . The increase in components in multilevel converters results in a corresponding increase in the number of valid commutation states, and thus in smoother changes in the state variables of the system and its consequent reduction in *dv/dt* of the output voltage.Among many existing multilevel topologies, the dual con- verter has the advantage that two standard two-level converters can produce multilevel operation. However, the main disadvantage of the dual-converter topology is the need for a coupling transformer, not needed in other multilevel topologies for the same range of power and voltage.The generality of the proposed filtering technique using instantaneous active and reactive power can be applied to any transformer configuration scheme in the power substation. Multilevel converter technology can facilitate the industrial implementation because it reduces the specifications of the power electronics switches and the voltage stress *dv/dt* on the magnetic components like coupling transformers and/or inductors.

II. HARMONIC AND UNBALANCE COMPENSATION SYSTEM

On balanced three-phase systems feeding balanced linear loads, the instantaneous active and reactive terms of the complex power are constant and equal to $p(t)$ = 3VI cos (φ) and $q(t)$ = 3VI sin(φ) [10], whereas for similar balanced three-phase systems, the instantaneous active and reactive power with unbalanced nonlinear loads contains average and oscillating terms.

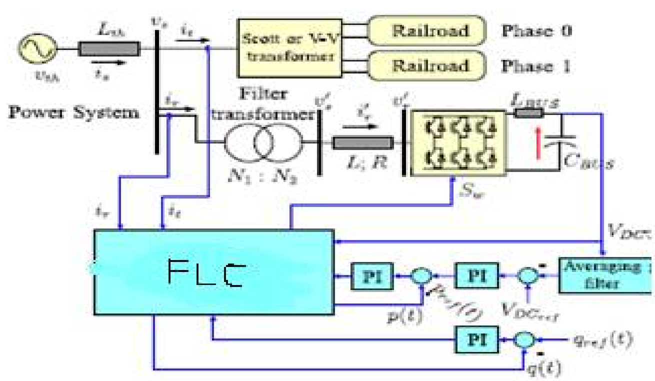

Fig..1. Proposed Compensation Scheme

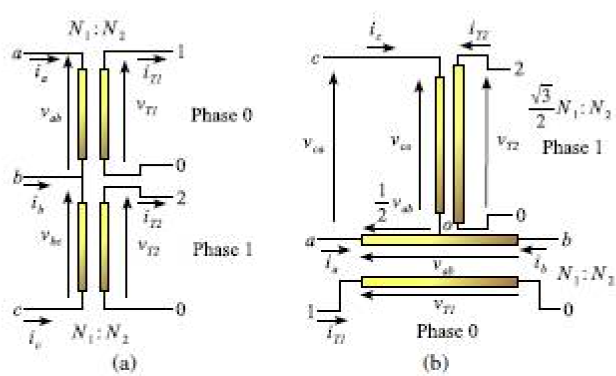

Fig.2.Traction Transformer Scheme. a) V-V-Transformer b) Scott Transformer

To compensate for load imbalance and reduce harmonic injection from the load to the supply system, the proposed controller, shown in Fig. 1, is aimed at keeping constant them instantaneous active and reactive power exchange with the supply. In this paper, this is achieved with a shunt active filter directly connected to the power system using a voltage step-up filter transformer. For the railway application, the power stage in the filter is a three-phase voltage source converter (VSC) with a rating between 10% and 15% of the distribution transformer rated power. The controller computes the total instantaneous active and reactive power taken by the combination of traction system total instantaneous active and reactive power drawn from the grid, acting in this way as a three-phase current balancer and harmonic filter. The p_{ref} consign is used to reduce the variations in the dc link of the filter's power stage. This will adjust automatically the power taken by the traction system plus the filter losses. The reactive power reference q_{ref} provides an additional degree of freedom that can be used to adjust the system's power factor.Fig. 2 shows the open delta (V-V) and Scott transformers used frequently to connect a traction substation to the electric grid. These connection schemes generate two single-phase networks from the three-phase power system. Each single-phase circuit is used to feed a 60–100 km rail track.The simulation of the steady state and dynamic behavior for the traction system under unbalance conditions and with harmonic current injection uses a space vector model of the open delta and Scott transformer, uncoupling the differential equations in the transformer model [11]. Additionally, the filter and its control have been modeled using a space vector representation [22].The power invariant space vector transformation is defined as and filter. In the proposed compensation scheme, the controller.

A. V-V Transformer Space Vector Model

For the ideal V-V transformer configuration shown in Fig. 2,its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws [1]

$$\vec{v}_s = \sqrt{\frac{2}{3}}\frac{N_1}{N_2}\left(v_{T1} - \alpha^2 v_{T2}\right)$$
$$\vec{i}_t = \sqrt{\frac{2}{3}}\frac{N_2}{N_1}\left[(1-\alpha)\, i_{T1} + (\alpha - \alpha^2)\, i_{T2}\right]. \quad (1)$$

B. Scott Transformer Space Vector Model

For the ideal Scott transformer shown in Fig. 2, its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws [1]:

$$\vec{v}_s = \sqrt{\frac{3}{2}}\frac{N_1}{N_2}\frac{1}{1-\alpha^2}\left(v_{T1} - j v_{T2}\right)$$
$$\vec{i}_t = \sqrt{\frac{2}{3}}\frac{N_2}{N_1}\left((1-\alpha)i_{T1} + \sqrt{3}\alpha^2 i_{T2}\right).$$

(2)

C. Active and Reactive Power Control

The DPC controller is based on the instantaneous apparent Power from the current and voltage space vectors definitions [12],

$$\vec{v}_s = \frac{N_1}{N_2}\vec{v}_s'; \ \vec{v}_r = \frac{N_1}{N_2}\vec{v}_r'; \ \vec{i}_r = \frac{N_2}{N_1}\vec{i}_r'$$
$$R = \left(\frac{N_1}{N_2}\right)^2 R_r; \ L = \left(\frac{N_1}{N_2}\right)^2 L_r.$$

(3)

D. Harmonics Filtering And Balance Using DPC

In a power system with a high short-circuit ratio ($ISC/IL \geq 20$), the voltage distortion produced by harmonic or unbalanced currents can be neglected . The unbalance is defined using the ratio between negative $V2$ and positive $V1$ sequence $V2/V1$. For three-phase voltage and current, a general expression including harmonics and unbalance is obtained with symmetrical components and Fourier expansions as follows:

E. Multilevel Compensation

Fig. 3 shows the open delta transformer (V-V) used to connect a traction substation to the electric grid, while the voltage space vector calculated in (11) is synthesized with the dual converter modulation technique presented [12].

III. FUZZY LOGIC CONTROLLER

The system dc link voltage response is very slow due to PI controller. In order to achieve fast dynamic response of dc link voltage, the FLC has been proposed in shunt controller part of the system. Because, the PI controller based scheme has produces a very slow dynamic response for the same system. Fuzzy memberships that are designed based on the eq.(4)

B (p) = IF R1 is S1 AND R2 is S2 ....Rn (4)

is Sn THEN S is C (p) (5)

Where, R1, R2.........Rn is the input variables vector S is the output or control variable n is the no. of fuzzy variables (N=5) F1, F2.......Fn is the fuzzy sets P =1, 2, 3....N N is the number of rules (N=5). To design an FLC, the error dc capacitor voltage (Vdc) and change in reference dc capacitor voltage error (ΔVdc) are considered. $ve\,fuzzy = vdc - vdc\,re.$

The proposed construction of a FLC as given in Fig.3.Actual crisp input values and its approximates are nearly closer to respective universes of its course. If the fuzzified inputs are designated by singleton fuzzy sets . The Fuzzy control rules are designed for a fuzzy set of the control input in each combination of fuzzy sets for Vdc and ΔVdc. The per phase fundamental active power estimation is added with eq. (3) and it is forwarded to reference source current generation. The p-q theory based currents are given to relay which is sensed to control the signals of shunt VSC circuit as shown in Fig.3.In this paper, instead of using conventional (PI) controller mentioned in references a FLC is being used for its transient

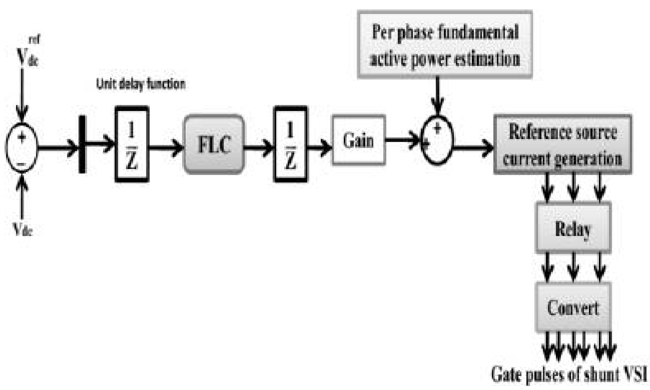

Fig.3.Propsed FLC Controller Scheme

Response to make MC-UPQC very fast in reducing the total harmonic distortions on source and load side voltages as well as currents on both the feeders. Here five labels of fuzzy subsets; negative large (NL), negative medium (NM), zero (ZR), positive medium (PM), positive large (PL). The control rule base table 1. In which the row and column represents the error and its changes respectively

Table 1 Fuzzy Rules

ΔVdc → Vdc↓		INPUT 2				
		NL	MN	ZR	PM	PL
INPUT 1	NL	NL	NL	NM	NM	ZR
	MN	NL	NM	NM	ZR	PM
	ZR	NM	NM	ZR	PM	PM
	PM	NM	ZR	PM	PM	PL
	PL	ZR	PM	PM	PL	PL

IV. SIMULATION RESULTS

The scheme shown in Fig. 1 is modeled using the space vector representation of the state variables, at a 10 kHz sampling rate. Both, the V-V and Scott transformers are included in these simulations. The railroad system is represented using the measured harmonic currents distribution, injected to the power system in the secondary side of each transformer. The three-phase power system is modeled using a space vector Thevenin equivalent. Also, space vector representations of the power transformer (V-V or Scott),

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three-phase (VSC), and the filter are used in the simulation. The parameters used in the simulations are shown in Table II.

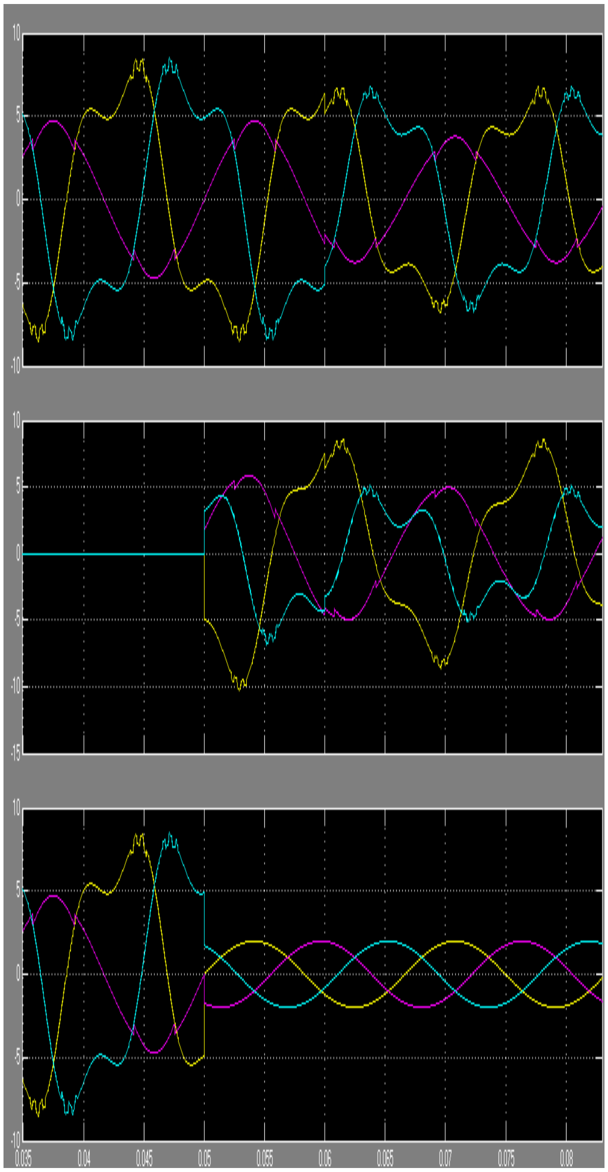

Fig. 4. Simulated active filter effect on the power system currents feeding a single phase rectifier load for the Scott and V–V connections. (a) V–V.

Fig 4 Simulated active filter effect on the power system currents feeding a single phase rectifier load for the Scott and V–V connections. (a) V–V. (b) Scott single-phase circuit with the other under no load,which is the most demanding operating condition.The active filter injects the harmonic content used by the single-phase railroad load. The proposed control scheme reduces by more than 96% the THD for both transformer connections. Fig.5 shows the simulated instantaneous currents flowing into the power system without compensation and with the proposed. Fig.6 shows how for pref constant, changes in qref affect the system variables. In this case, the main effect of the reactive power reference variation

is on the system's power factor, and can be observed in the relative current phase. The scheme shown in Fig. 1 is modeled using the space Vector representation of the state variables [13], at a 10 kHz Sampling rate. Both, the V-V and Scott transformers are included in these simulations. The railroad system is represented using the measured harmonic currents distribution, injected to the power system in the secondary side of each transformer [14].The three-phase power system is modeled using a space vector Thevenin equivalent. Also, space vector representations of the power transformer (V-V or Scott), three-phase (VSC), and the filter are used in the simulation. The parameters used in the simulations are shown in Table II.

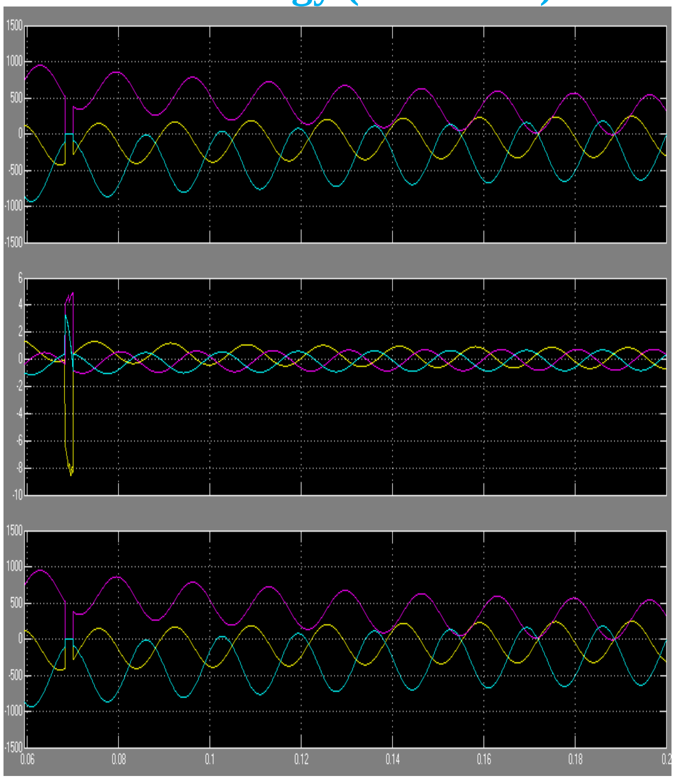

Fig.5. Simulated waveforms for the Scott transformer connection for different railroad load profiles

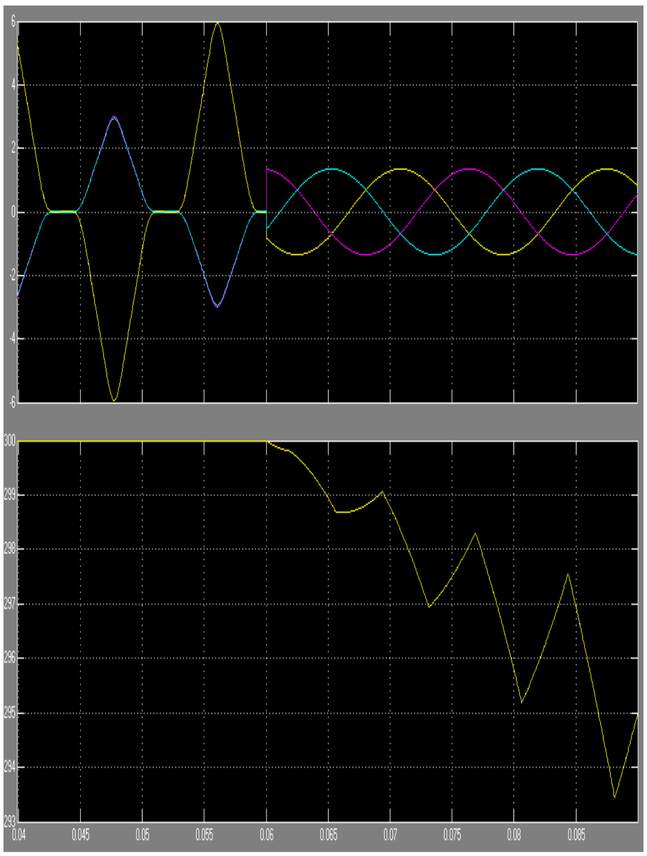

Fig.6. Effect on the line current's phase shift due to qref variation

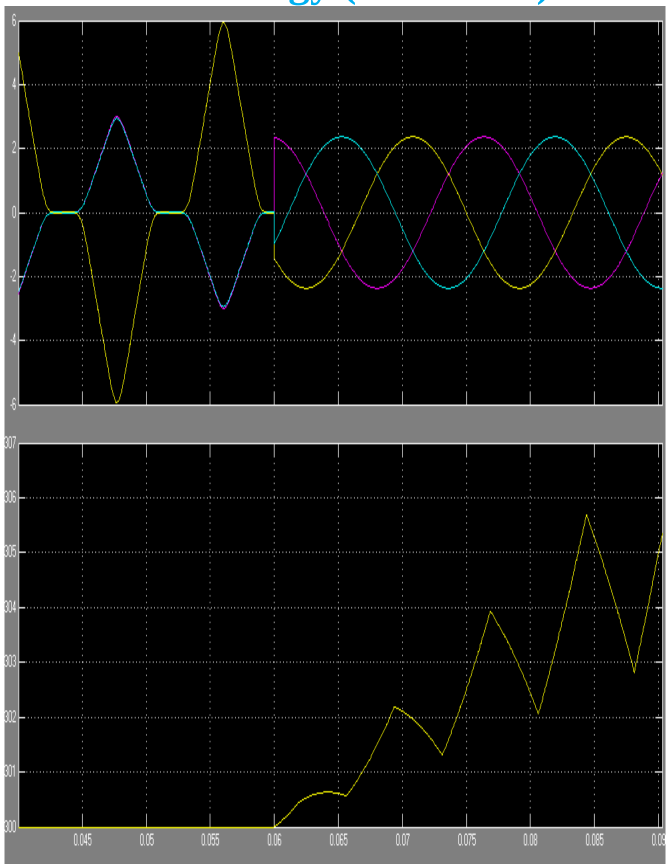

Fig. 7. Effect on the line current's phase shift due to qref variation

Fig. 7 shows how for pref constant, changes in qref affect the system variables. In this case, the main effect of the reactive power reference variation is on the system's power factor, and can be observed in the relative current phase. On the other hand, the dc-link voltage Vdc is barely influenced by changes in the reactive power reference.

Table- II Parameter of the Filter Scheme Model

Vth	Lth	Rth	Ltrx	C{1,2}	Vdc{1,2}
208V	0.1mH	1mΩ	10.0mH	1100mfd	200 –600 V

Table II shows the current total harmonic distortion (THD) and the unbalance relation between positive and negative sequences *I*2/*I*1 [35], for uncompensated and compensated cases using V-V and Scott transformers. The rectifier case uses a single-phase rectifier bridge-based load in one secondary of the main transformer. For the railroad case, the measured harmonic current spectrum is injected in one secondary phase. The simulation uses maximum unbalance by operating on one single-phase circuit with the other under no load, which is the most demanding operating condition. The active filter injects the harmonic content used by the single-phase railroad load. The proposed control scheme reduces by more than 96% the THD for both transformer connections.

. V. CONCLUSION

The proposed DPC-based compensation scheme reduces negative sequence currents injected by an uncompensated electric traction system using any power transformer connection. This technique can be used to reduce the current THD to values complying with international regulations, and additionally regulates the power factor observed in the common coupling point between the traction substation and the grid. Also, the compensation method based on the instantaneous power control algorithm with direct space vector representation, reduces the system's current THD to allowable ranges (<20%) and reduces the overall unbalance from 97% to 18% for worse-case operation. The compensation algorithm is able to control the power factor measured at the common coupling point under all considered conditions, with a very short transient thanks to the fast dynamic response of FLC. The distortion that remains in the compensated current is mainly due to the distortion in the grid voltage and the limitations of the switched nature of the filter's power stage, that is, unable to compensate very fast transients present in the traction current. Finally, a previously unreported space vector model for the Scott and open delta transformer connection has been introduced in this paper. The dual converter compensation scheme using an instantaneous power control algorithm with direct space vector computation reduces the unbalanced currents to allowable ranges (<10%) and reduces the overall unbalance from 42.8%to 3.8%.The dual converter's topology has been tested as an active filter, for increased power conversion employing lower voltage switching devices. The algorithm used in the control of the dual converter was an optimized version of the FLC. *dv/dt* is reduced by the increased number of levels generated by the dual converter topology.

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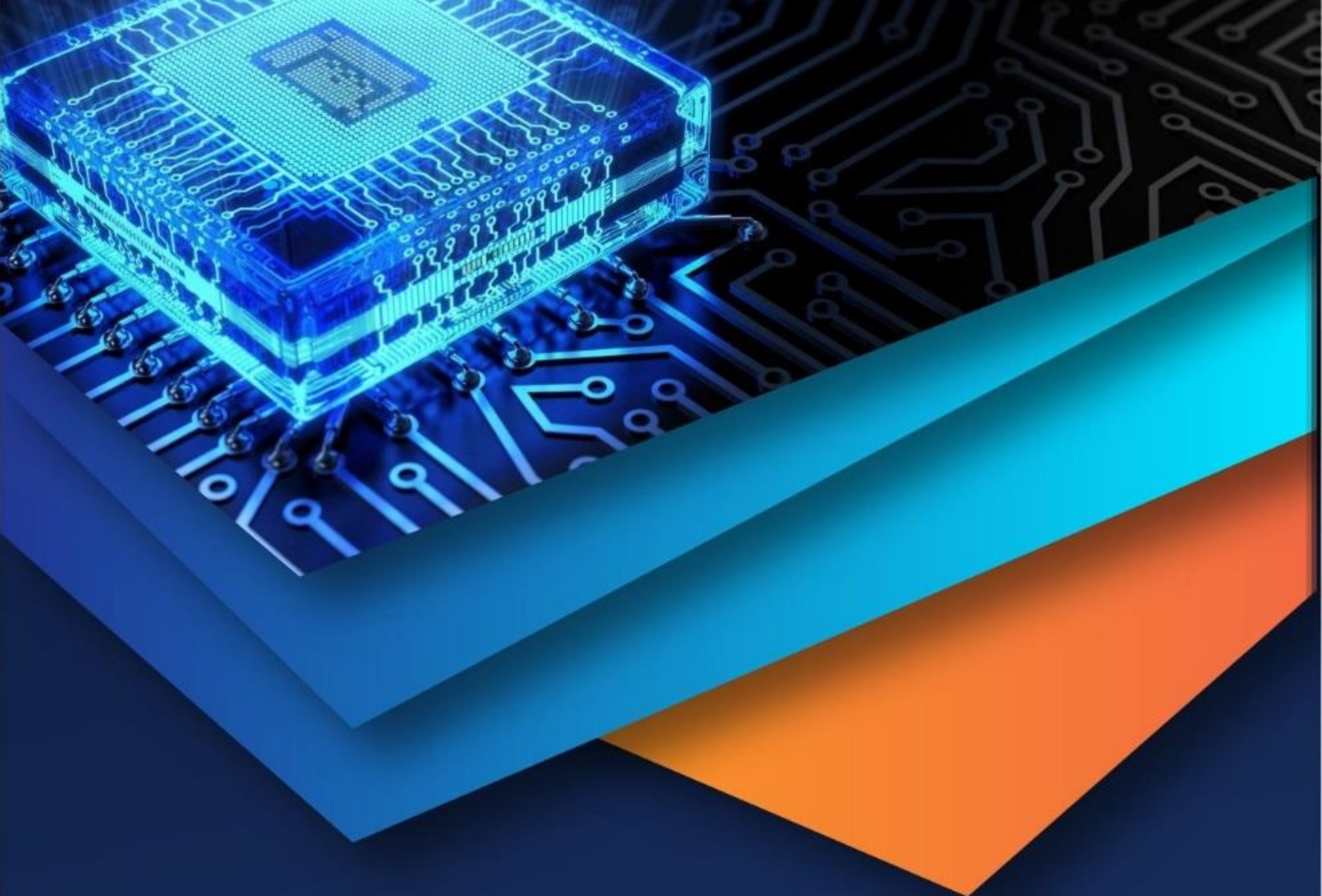

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