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

[1]M. Rama Pallavi, [2]M.Venkata Kishore, [3]K. Dinesh kumar reddy

SRIT Engineering college, proddatur.

***Abstract*: This paper presents a general filtering and unbalance compensation scheme for electric traction systems using a direct power control-based algorithm. For a balanced three-phase three- wire system, the proposed method is able to control the power flow exchange between the grid and the load so that the instantaneous complex power is maintained constant. As a consequence, any nonlinear unbalanced load is seen by the three-phase sup- ply as a balanced linear load. The proposed 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 scheme has been simulated and experimentally validated. The results from experimental and simulation tests show the controller advantages and the applicability of the proposed method in railway systems.**

***Index Terms:* Active filters, harmonics distortion, power control, rail transportation power system.**

I. Introduction

traction systems for passengers and freight 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 configurations , 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 contribute 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 themain three-phase system, depending on the transformer connection and harmonic order. Filters and unbalance compensators are therefore required to ensure proper system operation and to improve the power quality. 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. 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. phase shift 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 CharallaveCua 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 induc- tion 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%.The power range for the railroad application in this paper is around 10 MVA, and its implementation using multilevel con- verters 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. An important advantage of multilevel converters is the possibility to improve harmonic content of the synthesized voltage with a re- duced 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. 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 electronicsswitchesand the voltagestress 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 com- plex power are constant and equal to $p(t) = 3VI \cos(\varphi)$ and $q(t) = 3VI \sin(\varphi)$ whereas for similar balanced three-phase systems, the instantaneous active and reactive power with unbalanced nonlinear loads contains average and oscillaing terms. 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 the 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 rat- ing between 10% and 15% of the distribution transformer rated power.

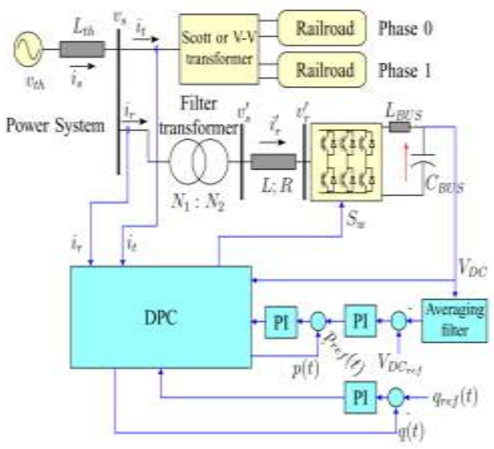


fig. 1. Proposed compensation scheme.

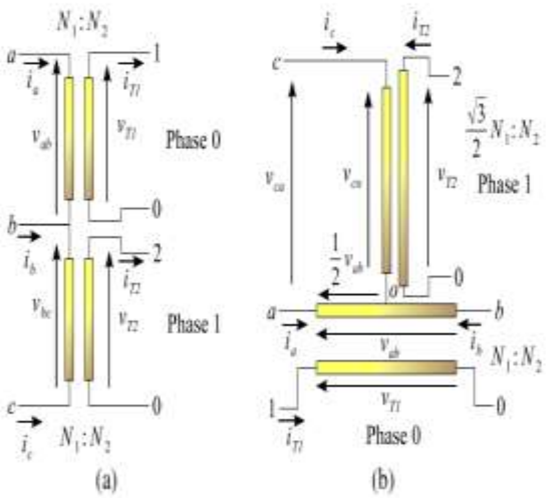


Fig. 2. Traction transformer schemes. (a) V-V transformer. (b) Scott transformer.

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 referenceF 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 mode. Additionally, the fil- ter and its control have been modeled using a space vector representation

$$\vec{x} = \sqrt{\frac{2}{3}}\left(x_a(t) + \alpha x_b(t) + \alpha^2 x_c(t)\right); \quad \alpha = e^{j\frac{2\pi}{3}}.$$

A V-V Transformer Space Vector Model:

For the ideal V-V transformer configuration shown , its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws.

$$v_{ab} = \frac{N_1}{N_2} v_{T1}; \; v_{bc} = \frac{N_1}{N_2} v_{T2}$$
$$i_a = \frac{N_2}{N_1} i_{T1}; \; i_c = \frac{N_2}{N_1} i_{T2}.$$

The voltage and current space vectors calculated in the trans- former's primary winding as function of the secondary winding voltages and currents are

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

B. Scott Transformer Space Vector Model:

For the ideal Scott transformer its model can be obtained considering the transformer ratio and using Ampere and Faraday Laws.

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

C . Active and Reactive Power Control

The DPC controller is based on the instantaneous apparent power from the current and voltage space vectors definitions

$$\vec{s} = \vec{v}_s \cdot \vec{i}_s^{*} = (v_{s\alpha} + j\, v_{s\beta}) \cdot (i_{s\alpha} + j\, i_{s\beta})^{*} = p + j$$

From Fig. 1, the active filter can be modeled as

$$\vec{v}_s' = \vec{v}_r' + R_r\, \vec{i}_r' + L_r \frac{d\vec{i}_r'}{dt}$$
$$\vec{i}_s = \vec{i}_r + \vec{i}_t$$

where

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

The apparent power variation needed to change from the uncompensated to the compensated state, gives the rectifier voltage apparent power due to a null vector in the rectifier voltage

$$\vec{\epsilon}_s(k) = \underbrace{p_{\text{ref}} - \Re e\{\vec{s}(k)\}}_{\epsilon_p(k)} + j\, \underbrace{q_{\text{ref}} - \Im m\{\vec{s}(k)\}}_{\epsilon_q(k)}.$$

synthesized in the converter using standard space vector modulation. As with other DPC algorithms, the reactor parameters are required for computing the estimated value of the power system voltages, the active and reactive power values and the updated value for the converter voltage indicated The proposed algorithm has low computational demands, pro- vides instantaneous correction of the active and reactive power in the point of common coupling, and reduces the ripple in the instantaneous power and currents. This produces low harmonic distortion and balances the load seen from the grid.

D. Harmonics Filtering and Balance Using DPC

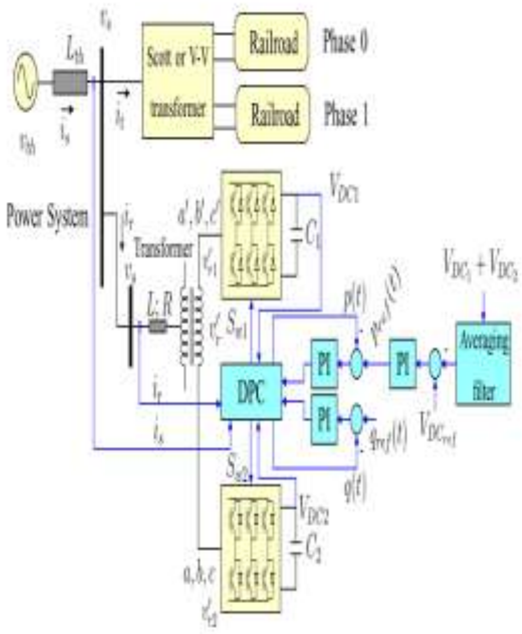
For three-phase voltage and current, a general expression including harmonics and unbalance is obtained with symmetrical components and Fourier expansions as follow the voltage distortion produced by harmonic or unbalanced currents can be neglect, The unbalance is defined using the ratio between negative

$$x_{a,b,c}(t) = \sum_{n=1}^{\infty}\left[\sqrt{2}X_{n1}\cos\left(n\omega t+\phi_{n1}-k\frac{2\pi}{3}\right)+\cdots\right.$$
$$\left.+\sqrt{2}X_{n2}\cos\left(n\omega t+\phi_{n2}+k\frac{2\pi}{3}\right)\right]$$
$$[a \quad b \quad c] \rightarrow k = [0 \quad 1 \quad 2];\ \forall x \in \{v, i\}.$$

The voltage and current space vectors are obtained by apply (1)–(13)

$$\vec{v}_s = \sqrt{3}\sum_{n=1}^{\infty}\left[V_{n1}\,e^{j(n\omega t+\alpha_{n1})} + V_{n2}\,e^{-j(n\omega t+\alpha_{n2})}\right]$$

$$\vec{i}_s = \sqrt{3}\sum_{m=1}^{\infty}\left[I_{m1}\,e^{j(m\omega t+\beta_{m1})} + I_{m2}\,e^{-j(m\omega t+\beta_{m2})}\right]$$



$$\vec{s} = 3\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\left[V_{n1}I_{m1}e^{j((n-m)\omega t+\alpha_{n1}-\beta_{m1})}+\cdots\right.$$
$$+V_{n1}I_{m2}e^{j((n+m)\omega t+\alpha_{n1}+\beta_{m2})}+\cdots$$
$$+V_{n2}I_{m1}e^{-j((n+m)\omega t+\alpha_{n2}+\beta_{m1})}+\cdots$$
$$\left.+V_{n2}I_{m2}e^{-j((n-m)\omega t+\alpha_{n2}-\beta_{m2})}\right].$$

eliminates the time dependence in for a strong voltage supply. Hence, the first and fourth terms in are constant when n = m, corresponding to harmonic filtering in the current sequence with strong voltage supply. The second and third terms for (n = m) in are zero for instantaneous constant complex power should be zero in other to obtain a constant instantaneous power. According for constant instantaneous power can be improved up to the harmonic voltage distortion THD 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 is synthesized with the dual converter modulation technique presented.

$$\sum_{n=1}^{\infty}\left[V_{n1}I_{n2}e^{j(2n\omega t+\alpha_{n1}-\beta_{n2})}+\cdots\right.$$
$$\left.+V_{n2}I_{n1}e^{-j(2n\omega t+\alpha_{n2}-\beta_{n1})}\right]=0.$$

To obtain zero in (17) the following relations need isfied:

$$V_{n1}I_{n2}=0,\ \text{and}\qquad V_{n2}I_{n1}=0.$$

III. EXTENSION BY USING FUZZY LOGIC CONTROL:

In recent years, the number and variety of applications of fuzzy logic have increased significantly. The applications range from consumer products such as cameras, camcorders, washing machines, and microwave ovens to industrial process control, medical instrumentation, decision-support systems, and portfolio selection.

To understand why use of fuzzy logic has grown, you must first understand what is meant by fuzzy logic.

Fuzzy logic has two different meanings. In a narrow sense, fuzzy logic is a logical system, which is an extension of multivalve logic. However, in a wider sense fuzzy logic (FL) is almost synonymous with the theory of fuzzy sets, a theory which relates to classes of objects with unsharp boundaries in which membership is a matter of degree. In this perspective, fuzzy logic in its narrow sense is a branch of fl. Even in its more narrow definition, fuzzy logic differs both in concept and substance from traditional multivalve logical systems.

In fuzzy Logic Toolbox software, fuzzy logic should be interpreted as FL, that is, fuzzy logic in its wide sense. The basic ideas underlying FL are explained very clearly and insightfully in Foundations of Fuzzy Logic. What might be added is that the basic concept underlying FL is that of a linguistic variable, that is, a variable whose values are words rather than numbers. In effect, much of FL may be viewed as a methodology for computing with words rather than numbers. Although words are inherently less precise than numbers, their use is closer to human intuition. Furthermore, computing with words exploits the tolerance for imprecision and thereby lowers the cost of solution.

Another basic concept in FL, which plays a central role in most of its applications, is that of a fuzzy if-then rule or, simply, fuzzy rule. Although rule-based systems have a long history of use in Artificial Intelligence (AI), what is missing in such systems is a mechanism for dealing with fuzzy consequents and fuzzy antecedents. In fuzzy logic, this mechanism is provided by the calculus of fuzzy rules. The calculus of fuzzy rules serves as a basis for what might be called the Fuzzy Dependency and Command Language (FDCL).

Although FDCL is not used explicitly in the toolbox, it is effectively one of its principal constituents. In most of the applications of fuzzy logic, a fuzzy logic solution is, in reality, a translation of a human solution into FDCL.

A trend that is growing in visibility relates to the use of fuzzy logic in combination with neuron computing and genetic algorithms. More generally, fuzzy logic, neuroncomputing, and genetic algorithms may be viewed as the principal constituents of what might be called soft computing. Unlike the traditional, hard computing, soft computing accommodates the imprecision of the real world.

The guiding principle of soft computing is: Exploit the tolerance for imprecision, uncertainty, and partial truth to achieve tractability, robustness, and low solution cost. In the future, soft computing could play an increasingly important role in the conception and design of systems whose MIQ (Machine IQ) is much higher than that of systems designed by conventional methods.

Among various combinations of methodologies in soft computing, the one that has highest visibility at this juncture is that of fuzzy logic and neuro computing, leading to neuro-fuzzy systems. Within fuzzy logic, such systems play a particularly important role in the induction of rules from observations. An effective method developed by Dr. Roger Jang for this purpose is called ANFIS (Adaptive Neuro-Fuzzy Inference System). This method is an important component of the toolbox.

The fuzzy logic toolbox is highly impressive in all respects. It makes fuzzy logic an effective tool for the conception and design of intelligent systems. The fuzzy logic toolbox is easy to master and convenient to use. And last, but not least important, it provides a reader friendly and up-to-date introduction to methodology of fuzzy logic and its wide ranging applications.

WHAT IS FUZZY LOGIC?

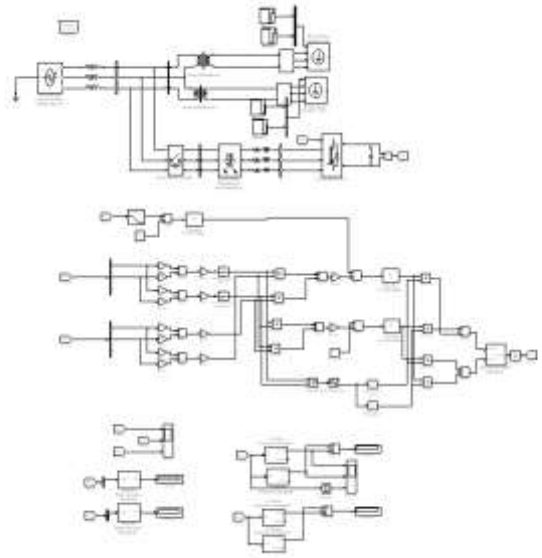
Fuzzy logic is all about the relative importance of precision: How important is it to be exactly right when a rough answer will do?

You can use Fuzzy Logic Toolbox software with MATLAB technical computing software as a tool for solving problems with fuzzy logic. Fuzzy logic is a fascinating area of research because it does a good job of trading off between significance and precision—something that humans have been managing for a very long time.

In this sense, fuzzy logic is both old and new because, although the modern and methodical science of fuzzy logic is still young, the concept of fuzzy logic relies on age-old skills of human reasoning.

IV. Simulation Results

Simualation diagram for base paper :



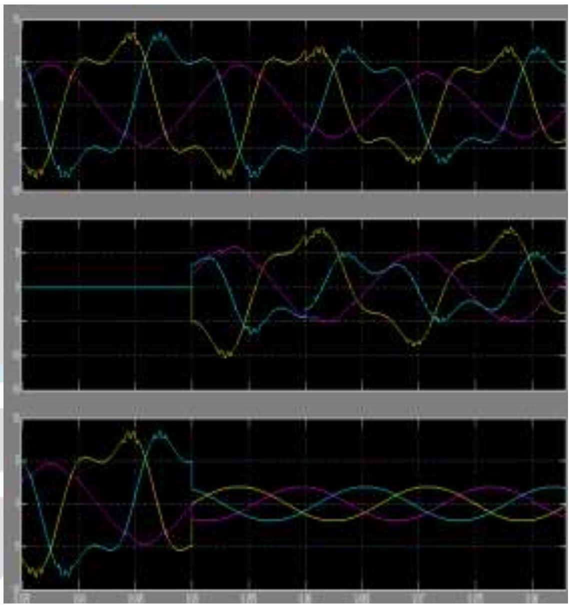
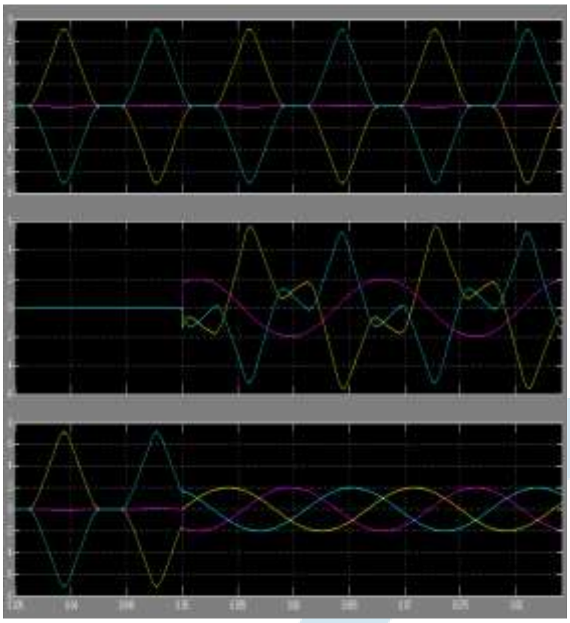
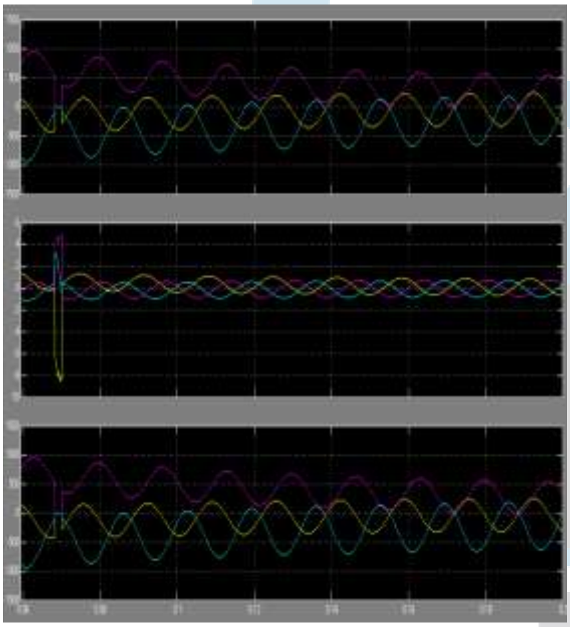


Fig:4.1 Simulated active filter effect on the power system currents feeding a single phase rectifier load for the Scott and V–V connections. (a) V–V.

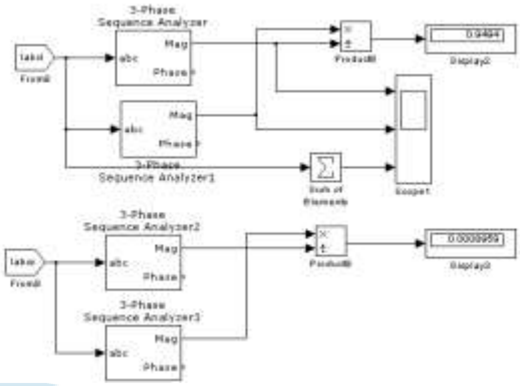


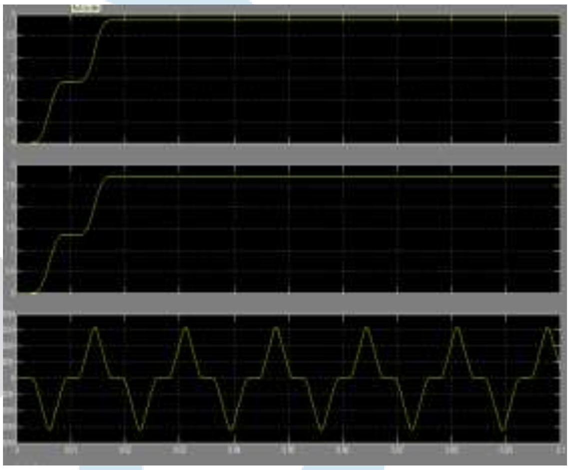
. Fig:4.2 Simulated active filter effect on the power system currents feeding asingle phase rectifier load for the Scott and V–V connections. . (b) Scott.

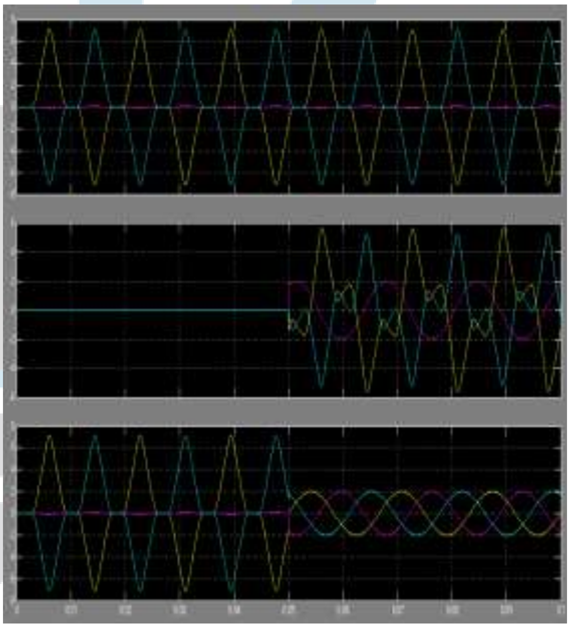


. fig: 4.3 Simulatedwaveforms for the Scott transformer connection for different railroad load profiles.

Simulation diagram for using fuzzy logic control :







4.4 Simulated active filter effect on the power system currents feeding asingle phase rectifier r the Scott and V–V connections using fuzzy logic

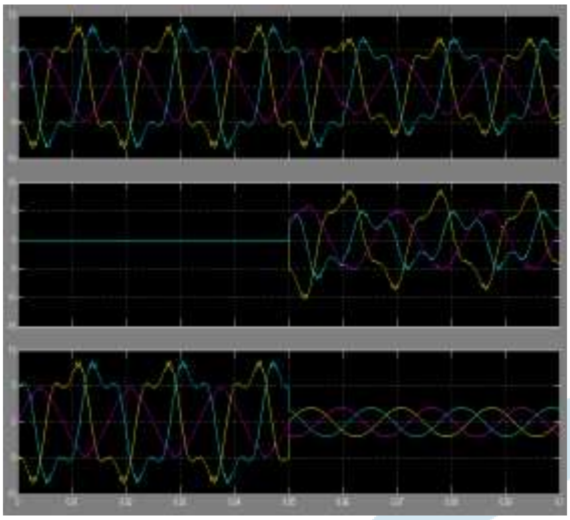


fig: 4.5 Simulat edwaveforms for the Scott transformer connection for different railroad load profiles using fuzzy logic

IV Conclusion

The proposed DPC-based compensation scheme reduces neg- ative 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 reg- ulates the power factor observed in the common coupling point between the traction substation and the grid. Also, the com- pensation 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 opera- tion. The compensation algorithm is able to control the power factor measured at the common coupling point under all con- sidered conditions, with a very short transient thanks to the fast dynamic response of DPC. 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.

power control algorithm with direct space vector com- putation 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 fil- ter, 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 DPC. dv/dt is re- duced by the increased number of levels generated by the dual converter topology.

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