Dual Converter Active Filter and Balance Compensation on Electric Railway Systems using the Open Delta Transformer Connection

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***Abstract*—This work presents a filtering and unbalance compensation scheme for electric traction systems with open delta transformers using dual converters. The proposed method uses an active filter controlled with the instantaneous active and reactive power, to reduce the harmonic current distortion and the negative sequence present in the railway system under unbalanced operation in steady state. The dual converter controls the voltage level in each sub converter. The modulation method used is commonly known from literature and the option of clamping one of the sub converters is exploited to minimize the switching. The use of dual-converters in active filters and balance compensation reduces the voltage level across the power devices. The dual converter is implemented using conventional two level three phase converters. The method has been experimentally validated, and the results prove the proposed controller advantages.**

***Index Terms*—Power system harmonics, Active filters, Power transformers, Rail transportation power systems.**

I. Introduction

Electric traction systems for passengers and freight use different transformation schemes in order to convert the three-phase supply system into two single-phase systems. The more common three phase to two single phase conversion schemes use transformers connected in open delta ($V-V$ connection), Scott or Le Blanc configurations [1], [2]. In a practical application, the railroad load associated with each single-phase circuit does not compensate each other, 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, and injects current harmonics into the single-phase supply system. Those harmonics propagate into the main three-phase system depending on the transformer connections and the harmonic order. The harmonic content injected into the main three-phase system contribute to the total system unbalance [3].

The use of filters and unbalance compensation is required to reduce or eliminate the harmonic contamination and to reduce the unbalance, in order to ensure proper system operation and improve the electric service quality [4].

Dual converters continue to be a topic of intense research [5] and several modulation techniques have been reported with distinct advantages over conventional two-level converters [6], [7]. An important advantage of dual converters is the possibility to improve the harmonic content, obtained for the synthesized voltage with a reduced amount of commutations. In addition, it is possible to reach higher voltage levels and higher power rating with power devices having lower breakdown voltages [6]. The increase in components in dual converters results in an increase in the number of valid commutation states, and thus in smoother changes in the state variables of the system and a reduction in the output voltage's dv/dt. Among many existing multilevel topologies, the dual converter structure has the advantage that multilevel operation can be obtained by using two standard two-level converters.

This work presents an analysis of the dual-converter filtering and compensation schemes and proposes practical and economical solutions to the problems caused by harmonics and load unbalance associated with the normal operation of electric transport systems, using transformers in open delta configuration. The active filter used to reduce the load-generated harmonics is controlled to simultaneously compensate the supply network current unbalance. The proposed scheme uses a vector control technique based on direct power control (DPC) to instantaneously regulate the active and reactive power components, in order to correct unbalance and harmonic distortion at the same time [8].

The control strategies presented in this work are experimentally validated using a modular power electronic system able to emulate the operating conditions of the electric traction system, the transformer connected in open delta configuration and the filtering and load balancing converters [9].

II. Harmonic and unbalance compensation system

Figure 1 shows the proposed control scheme used to compensate the unbalance and harmonic distortion injected by the railroad load into the power system. A parallel active filter is used, that is directly connected to the power system bar using a voltage step-up transformer. The power converter is configured as an active three-phase PWM rectifier.

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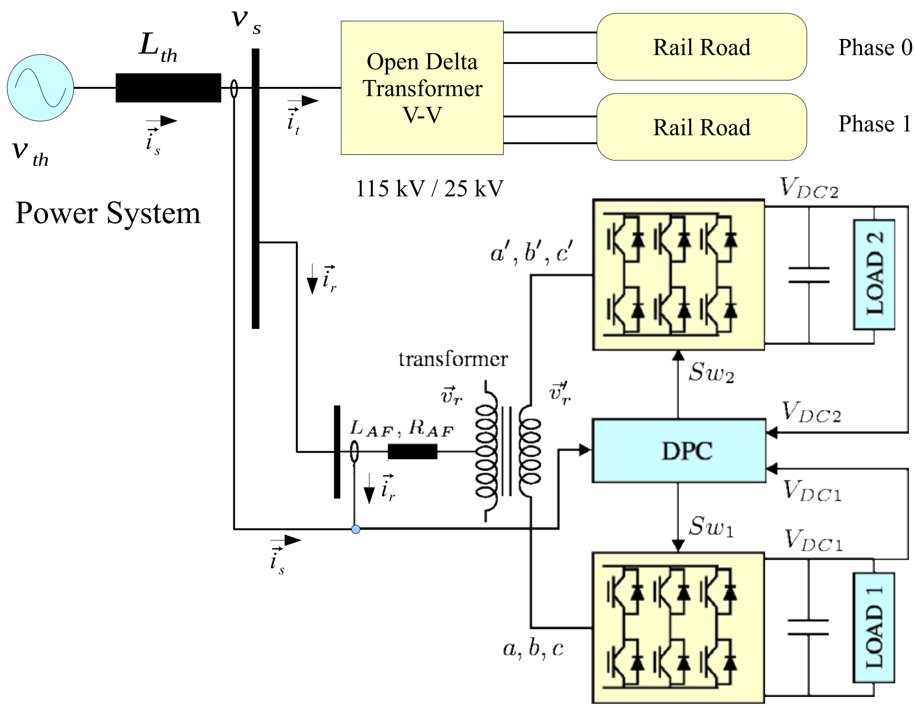

Fig. 1: Compensation scheme

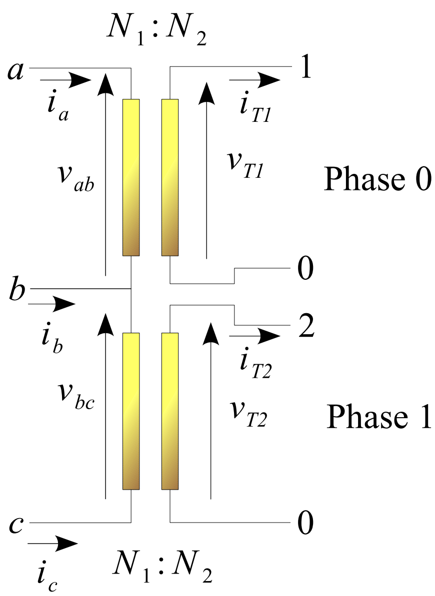

Fig. 2: Open Delta (V-V) transformer

Figure 2 shows the open delta transformer ($V - V$) used to connect a traction sub-station to the electric grid. This connection provides two single-phase systems from the main three-phase national grid, and each single-phase system is used to feed a rail track of 60 to 100 km.

III. Transformer's space vector model

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

$$v_{ab} = \frac{N_1}{N_2}\, v_{T1};\; v_{bc} = \frac{N_1}{N_2}\, v_{T2}$$
$$i_a = \frac{N_2}{N_1}\, i_{T1};\; i_c = \frac{N_2}{N_1}\, i_{T2} \tag{1}$$

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

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

were

$$\alpha = e^{j\frac{2\pi}{3}} \tag{3}$$

IV. Active and reactive power control

The DPC controller is based on the instantaneous apparent power from the current and voltage space vector definitions [10]:

$$\vec{s} = \vec{v}_s \cdot \vec{i}_s^{\,*} = \left(v_{s\alpha} + j\, v_{s\beta}\right)\cdot\left(i_{s\alpha} + j\, i_{s\beta}\right)^* = p + jq \tag{4}$$

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

$$\vec{v}_s = \vec{v}_r + R\,\vec{i}_r + L\frac{d\vec{i}_r}{dt} \tag{5}$$

$$\vec{i}_s = \vec{i}_r + \vec{i}_t \tag{6}$$

A discrete time version of this equation is obtained by replacing the derivative with a first order Euler approximation, and the estimated supply current for the next control cycle becomes

$$\widehat{\vec{i}}_s(k+1) = \vec{i}_s(k) + \Delta\widehat{\vec{i}}_s(k) \tag{7}$$

where

$$\Delta\widehat{\vec{i}}_s(k) = \frac{T_s}{\hat{L}}\left[\widehat{\vec{v}}_s(k) - \widehat{\vec{v}}_r(k) - \hat{R}\,\vec{i}_s(k)\right] \tag{8}$$

From (4), the estimated active and reactive power for the next sampling period can be written as,

$$\begin{aligned} \vec{s}(k+1) &= \vec{s}(k) + \Delta\vec{s}(k) = \\ &= \vec{s}(k) + \Delta p(k) + j\Delta q(k) = \\ &= \vec{v}_s(k)\cdot\vec{i}_s(k)^* + \Delta\widehat{\vec{v}}_s(k)\cdot\vec{i}_s(k)^* + \cdots \\ &\cdots + \widehat{\vec{v}}_s(k+1)\cdot\Delta\widehat{\vec{i}}_s(k)^* \end{aligned} \tag{9}$$

Replacing (8) in (9), the change in apparent power is:

$$\begin{aligned} \Delta\vec{s}(k) &= \Delta\widehat{\vec{v}}_s(k)\cdot\vec{i}_s(k)^* + \cdots \\ \cdots &+ \widehat{\vec{v}}_s(k+1)\cdot\frac{T_s}{\hat{L}}\left[\widehat{\vec{v}}_s(k) - \widehat{\vec{v}}_r(k) - \hat{R}\,\vec{i}_s(k)\right]^* \end{aligned} \tag{10}$$

For a sinusoidal voltage source power supply, the estimated $\widehat{\vec{v}}_s(k+1)$ is obtained by rotating space vector $\vec{v}_s$ in $\Delta\theta = \omega T_s$ rads.

$$\widehat{\vec{v}}_s(k+1) = \vec{v}_s(k)\cdot e^{j\omega T_s} \tag{11}$$

$$\Delta\widehat{\vec{v}}_s(k) = \vec{v}_s(k)\,\left(e^{j\omega T_s} - 1\right) \tag{12}$$

The complex apparent power $\vec{s}(k)$ is a function of the supply voltage, and also depends on the rectifier voltage $\widehat{\vec{v}}_r(k)$ that can be manipulated to obtain the commanded value $p_{ref} + j\,q_{ref}$. If $\Delta\vec{s}_0(k)$ is defined as the term that does not depend on $\widehat{\vec{v}}_r(k)$, the following change in active and reactive power is obtained

$$\begin{aligned} \Delta\vec{s}_0(k) &= \frac{T_s}{\hat{L}}\left|\vec{v}_s(k)\right|^2\cdot e^{j\omega T_s} + \cdots \\ \cdots &+ \vec{v}_s(k)\cdot\vec{i}_s(k)^*\left[\left(1 - \frac{T_s\hat{R}}{\hat{L}}\right)e^{j\omega T_s} - 1\right] \end{aligned} \tag{13}$$

For a given reference in active and reactive power the change in power for proper compensation becomes a function of the converter voltage $\widehat{\vec{v}}_r(k)$. The apparent power variation required to change from the actual to the demanded value in the following sampling period, p_{ref} and q_{ref}, are given by the following expressions

$$\Delta\vec{s}(k) = \Delta\vec{s}_0(k) - \frac{T_s}{\hat{L}}\left[\widehat{\vec{v}}_s(k+1)\cdot\widehat{\vec{v}}_r(k)^*\right] \tag{14}$$

$$\vec{\epsilon}_s(k) = \underbrace{p_{ref} - \Re e\{\vec{s}(k)\}}_{\epsilon_p(k)} + j\underbrace{q_{ref} - \Im m\{\vec{s}(k)\}}_{\epsilon_q(k)} \tag{15}$$

In the optimum vector selection scheme (OVSS), also known as predictive direct power control, a cost function is evaluated for a set of the converter voltages $\vec{v}_r$, and the value of this voltage providing the minimum value for the cost function is employed in the next control cycle [11]–[13]. In this case the cost function is

$$J(k) = \eta_p\left(\epsilon_p(k) - \Re e\left|\Delta\vec{s}(k)\right|\right)^2 + \eta_q\left(\epsilon_q(k) - \Im m\left|\Delta\vec{s}(k)\right|\right)^2 \tag{16}$$

where η_p and η_q control the relative importance of the active and reactive parts in the system.

The proposed control technique is based on the selection of the dual converter vector that minimizes the cost function (16) expressed by the active and reactive power errors. However, since zero is the global minimum for the cost function, instead of going through numerous iterations with suitable candidate vectors, the proposed technique computes the optimal voltage vector using a closed form expression. Forcing to zero the cost function (16), $J(k) = 0$,

$$\vec{\epsilon_s}(k) - \Delta\vec{s}(k) = 0 \tag{17}$$

Replacing (14) and (15) in (17)

$$\Delta\vec{s}_0(k) - \frac{T_s}{\hat{L}}\left[\widehat{\vec{v}}_s(k+1)\cdot\widehat{\vec{v}}_r(k)^*\right] = \epsilon_p(k) + j\epsilon_q(k) \tag{18}$$

Finally, substituting (11) into (18), the absolute optimum converter voltage required to attain the commanded active and reactive power becomes

$$\widehat{\vec{v}}_r(k) = \widehat{v}_{r\alpha}(k) + j\,\widehat{v}_{r\beta}(k) = \frac{\hat{L}}{T_s}\left[\frac{\Delta\vec{s}_0(k) - \vec{\epsilon}_s(k)}{\vec{v}_s(k)\cdot e^{j\omega T_s}}\right]^* \tag{19}$$

This voltage is synthesized in the converter using standard space vector modulation (SVM) [14]. As with other predictive DPC algorithms, the reactor parameters are required for computing the estimated value of the power system voltages, the active and reactive power and the updated value for the converter voltage in (19).

The proposed algorithm has many advantages over existing methods, among them it provides an instantaneous correction of the active and reactive power flowing into the converter, reduces the ripple in the instantaneous power and currents, resulting in a low harmonic distortion and have low computational demands.

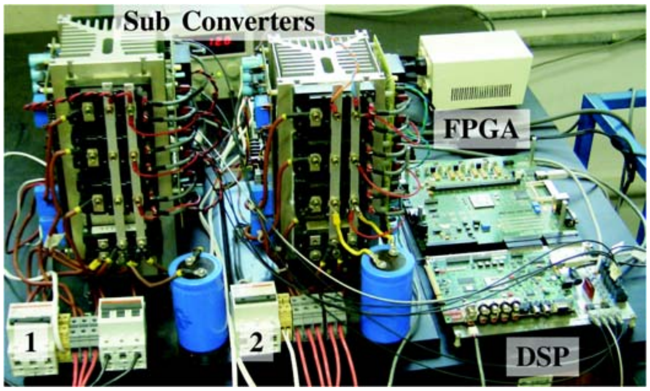

Fig. 3: Experimental rig

V. Experimental results

For the experimental test, the proposed algorithm is implemented on a custom built floating point DSP (ADSP-21061-40 MHz) based test-rig. The power stage uses six 50 A, 1200 V, IGBTs with two 2200 μF 400 V series connected capacitors in the DC link. The input inductors have 7 mH; the PWM signals are provided by a motion co-processor ADMC-201 operating at 10 kHz. The railroad load is implemented in only one single phase circuit using a single phase rectifier bridge with an R-L (50-200 Ω, 40 mH) load on the DC side. The sampling frequency is synchronized at the beginning of each PWM cycle. Fig. 3 shows the power module and the DSP based processing unit. The electrical parameters for the power circuit in the experimental tests are shown in Table I. The open delta ($V-V$) transformer connections are built using two single-phase 480 – 240 : 240 – 120 V, 1 kVA transformers.

TABLE I: Parameter test-rig

R_{rec}	L_{rec}	C	V_{DC}	T_s	V
$20\,m\Omega$	$7.0\,mH$	$1100\,\mu F$	$200 \sim 600V$	$100\,\mu s$	$208\,V$

f	f_s	R_{LOAD}	C_{LOAD}	L_{LOAD}
$60\,Hz$	$100\,kHz$	$50\,\Omega$	$2200\,\mu F$	$17\,mH$

Figure 4 presents the current and voltage waveforms, the current unbalance and the harmonic spectra measured on the three phase open delta transformer test bench feeding a non-linear load, with and without the proposed compensation scheme. The non-linear load is an uncontrolled single-phase diode rectifier with a $100\,\Omega$ resistive load. Comparing the compensated and the uncompensated results, it can be observed that the compensator increases the phase a current, eliminating unbalance and reducing harmonic content. The vector diagrams show that the phase voltage and current signals are balanced and in-phase when the compensator is operating. The compensator reduces the current unbalance from 42.8% (uncompensated value) to 3.8% (compensated value). The compensator reduces the current THD to values below 6.3% in all phases. It achieves a significant reduction in the fifth and seventh harmonics, which are the more significant components present in the harmonic spectra generated by the vector controlled converters used in locomotives.

VI. Conclusions

The proposed compensation scheme reduces the negative sequence currents that circulate in the uncompensated system feeding an electric traction system. The scheme reduces the current THD to values allowed by in the international regulations, and increases the power factor observed in the coupling point between the traction system and the grid. The proposed compensation scheme implementation using an instantaneous power control algorithm with direct space vector calculation reduces the unbalanced currents to tolerable levels ($< 10\%$) and reduces the overall current unbalance from 42.8% to 3.8%. The compensation algorithm is able to control the power factor measured at the coupling point under all considered conditions. The dual converter's topology has been tested as a controlled rectifier, for increased power conversion employing lower voltage switching devices. The algorithm used for the control of the dual converter is an optimized version of the direct power control (DPC). The experimental results show that there is a compromise between the amount of unbalance correction and harmonic reduction that can be achieved. This is due to the finite amount of energy stored in the active filter in its inductance and dc-link capacitor. The flexibility of the modulation strategies result in a reduction of the number of simultaneous switching instances in the sub converters. The $\frac{dv}{dt}$ is reduced due to the increased number of levels generated by the dual converter topology.

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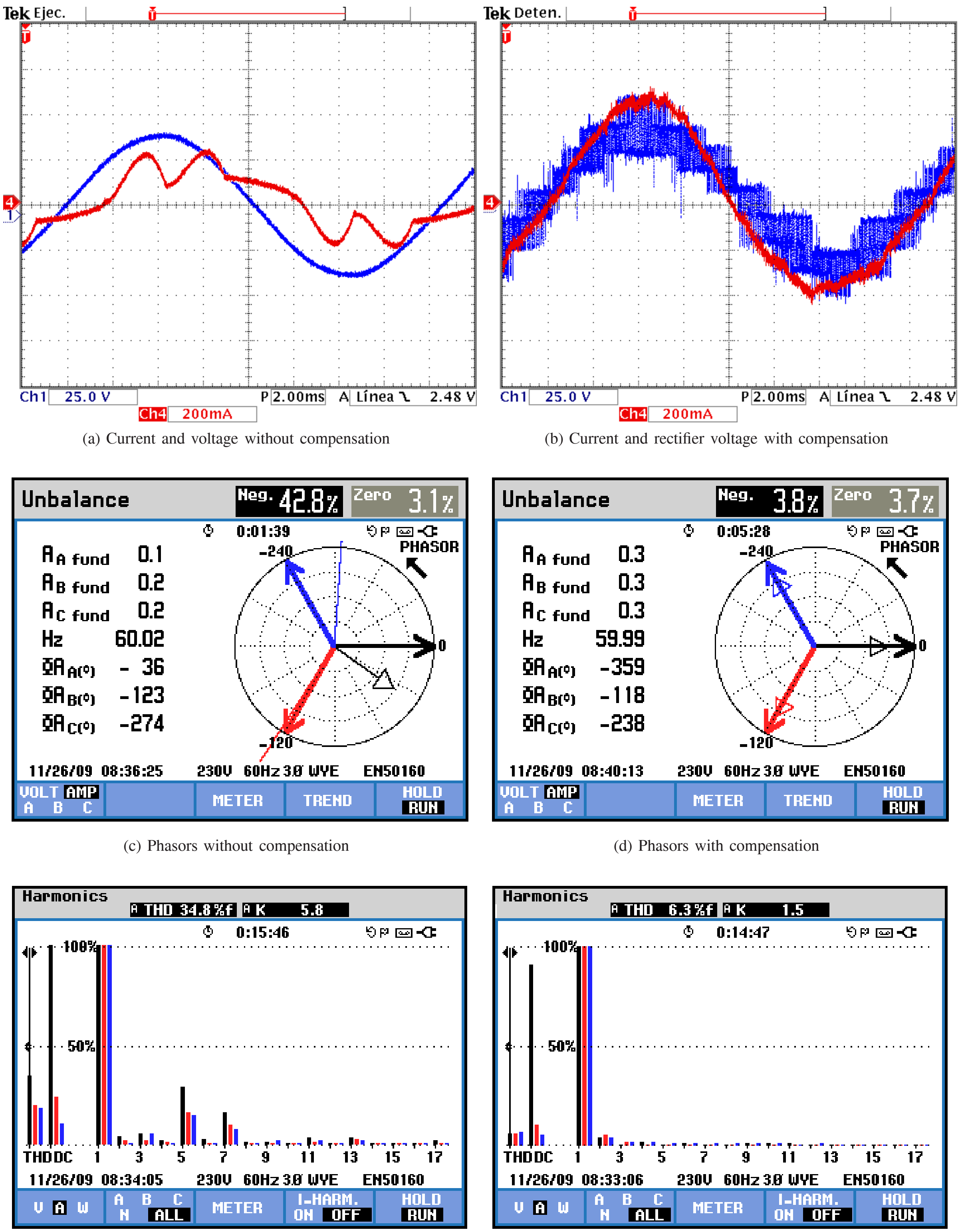

(a) Current and voltage without compensation

(b) Current and rectifier voltage with compensation

(c) Phasors without compensation

(d) Phasors with compensation

(e) Harmonics without compensation

(f) Harmonics with compensation

Fig. 4: Experimental results with and without compensation.

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