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Advanced Universal Power Quality Conditioning Systems in Three-Phase Four-Wire supply networks Under Non-Ideal Waveforms

***Abstract**. This paper presents negative impacts of capacitive loads (with very low Z_L) on the shunt active power filter accuracy. First, an advanced universal power quality conditioning system (A-UPQS) is proposed for three-phase four-wire systems under non-ideal waveforms. Considering the suggested compensation algorithm, the advanced UPQS is able to suppress source-end current harmonics caused due to the distorted-unbalanced load-terminal voltages. Moreover, an independent single-phase converter is suggested at the load-end in order to regulate the DC-link voltage. Unlike a previous proposition of a three-phase converter at the source-end, the new suggestion will be able to regulate the DC-link without any distortion. Therefore, the source-end three-phase currents would be purely sinusoidal. Simulations show that the proposed advanced UPQS performs effectively in line with the desirable outcomes.*

***Streszczenie.** Zbadano wpływ obciążenia pojemnościowego na pracę filtru aktywnego. Zaproponowano zaawansowany system kondycjonowania jakości energii w sieci trójfazowej czteroprzewodowej. Uzyskano tłumienie harmonicznych wynikających z wpływu obciążenia. (**Zaawansowany uniwersalny system kondycjonowania jakości energii w sieci trójfazowej czteroprzewodowej**)*

Keywords: Unified Power Quality conditioning System, Load-Terminal Voltage, DC bus, A-UPQS.
Słowa kluczowe: jakość energy, filtry aktywne.

I. Introduction

Rapid growth of the power electronic loads yields lots of power quality problems such as errors in measuring devices, amplifying of harmonics due to the wrong operation of the active power filters, malfunction of electronic equipment, overheating of transformers and diminution of power system efficiency [1]. In a micro-grid, oscillating power may appear due to the oscillation in the load or oscillation in the renewable energy sources like wind power. Micro-grids mainly have torsional torque vibration that should be damped to avoid frequency variation [2]. In [3] it is shown that shunt active filters are used to eliminate power oscillations. Due to the fact that shunt active filter produces unacceptable performance in the presence of capacitive loads, some modern solutions in form of unified power quality controller (UPQC) and universal power quality conditioning systems (UPQS) are proposed for three-phase three-wire networks in [4],[5]. Such solutions under balanced linear load condition generate satisfactory outcomes in the four-wire supply networks. Nevertheless, when the load-terminal voltages are unbalanced or distorted, these solutions would not lead to a satisfactory source-end zero current cancellation and harmonics suppression [6]. This paper intends to perform vital corrections on the shunt filter activating algorithm for the aforementioned unified power compensators. It seems to be essential to do so for a satisfactory harmonics alleviation and reactive power compensation in three-phase four-wire systems [7]. Here is proposed an advanced universal power quality conditioning system (A-UPQS) which leads to purely sinusoidal source-end currents under both distorted-unbalanced load-terminal voltages and capacitive load conditions. A compensation algorithm is a commanding sub-system for the shunt filter, extracting the reference signals from load-terminal currents and voltages at the point of common coupling.

One of the important time-domain power theories is the OS (optimal solution) which is proposed by Czarnecki in [8] and simply implemented only for three-phase three-wire balanced systems. A complementary optimal solution method which is applicable to three-phase four-wire balanced systems is proposed in [9].The generalized theory of instantaneous power definition (GTIP) as a well-known power theory is well-planned and formulated in [10]. The control algorithms based on these power theories result in unsatisfactory outcomes when the load-terminal voltages are unbalanced and distorted. So this paper proposes advanced GTIP (A-GTIP) as a solution to provide accurately references for active power filters. Moreover, by connecting the isolated DC-link voltage regulating converter to just one-phase at the load-terminal side, the current distortions and harmonics generated by independent single-phase converter would be nullified by the shunt filter of the proposed A-UPQS.

The paper is organized as follows. Section II describes the malfunctioning of the shunt active filters. In section III, the structure of general unified compensators is presented. By introducing a compensation algorithm based on advanced generalized theory of instantaneous power (A-GTIP) [11] in section IV, Advanced UPQS is proposed in three-phase four-wire systems. Effectiveness of the proposed A-UPQS is verified by Matlab/Simulink simulations.

II. Shunt active filter malfunction

Shunt active filter produces controlled current in order to compensate harmonic and unbalanced currents drawn by the non-linear loads. The principles of shunt current injection can be explained base on fig.1.

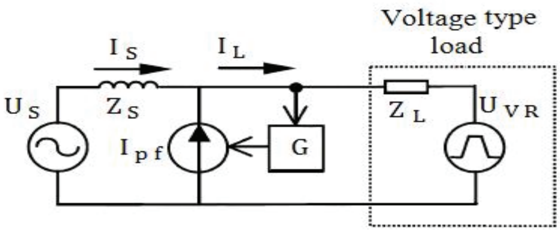

Figure1. Shunt active filter compensation of voltage type loads

If magnitude of injected current of shunt filter (Ipf) be equal to the load harmonics in reverse phase, the shunt active filter generates satisfactory outcomes and leads to purely sinusoidal source-end currents.

(1) $$\begin{cases} \begin{cases} I_{pf} = G(jw).I_L, G(jw) = \begin{cases} 0, w = w_1 \\ 1, w = wh \end{cases} \\ KCL: I_s = (1 - G(jw))I_L \\ KVL: U_s = Z_s I_s + Z_L(I_s + G(jw)I_L) + U_{VR} \end{cases} \\ \begin{cases} I_L = \dfrac{1}{1-G(jw)} * \dfrac{U_s - U_{VR}}{Z_s + \dfrac{Z_L}{1-G(jw)}} \\ I_s = \dfrac{U_s - U_{VR}}{Z_s + \dfrac{Z_L}{1-G(jw)}} \end{cases} \end{cases}$$

If for w=w$_h$, $\left.\frac{Z_L}{1-G}\right|_{w=w_h} \geq\geq Z_s|_{w=w_h}$, then I_L (load current) and I_S (source-end current) are obtained as follows:

(2) $$\begin{cases} I_L(w = w_h) = \dfrac{1}{0} * \dfrac{U_s - U_{VR}}{Z_s + \dfrac{Z_L}{0}} = \dfrac{U_s - U_{VR}}{Z_L} \\ I_s(w = w_h) = \dfrac{U_s - U_{VR}}{Z_s + \dfrac{Z_L}{0}} \approx 0 \end{cases}$$

Due to the fact that capacitive loaded diode rectifier has a very low Z_L, the upper equations would not be fulfilled and therefore, the shunt active filters cannot produce satisfactory outcomes. One solution is to insert high impedance on harmonic frequencies in order to compensate harmonic currents drawn in the case of capacitive loaded diode rectifiers as shown in fig.2.

(3) $$\begin{cases} U_{Sf} = K.G(jw).Is, G(jw) = \begin{cases} 0, w = w_1 \\ 1, w = wh \end{cases} \\ \begin{cases} KVL: U_s = Z_s I_s + Z_L I_s + U_{sf} + U_{VR} \\ I_s = \dfrac{U_s - U_{VR}}{Z_s + Z_L + K.G(jw)} \end{cases} \end{cases}$$

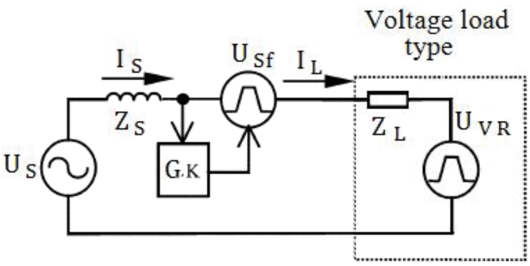

Figure 2. Series active filter supplying current and voltage type loads.

In equation (3) k is the impedance gain in harmonic frequencies. If $K \geq\geq |Z_s + Z_L|_{w=w_h}$ is fulfilled then the further result would be obtained:

(4) $$\begin{cases} I_s(w = w_h) = \dfrac{U_s - U_{VR}}{Z_s + Z_L + K.G(jw)} \approx 0 \\ U_{sf} \approx Z_L.I_L(w = w_h) + U_s(w = w_h) \end{cases}$$

Now, the combination of series and shunt active filter produce satisfactory outcomes and therefore, a full harmonic cancellation would lead to sinusoidal source-end currents.

III. Structure of General Unified Power Quality Controller

Basic structure of a general unified power quality conditioner (UPQC) as shown in fig.3 consists of the combination of series-active and shunt-active filters.

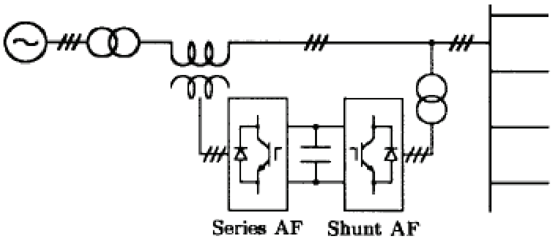

Figure 3. General unified power quality conditioner (UPQC)

• **Series Filter**: The series active power filters are used to compensate the source voltage deficiencies and forces capacitive load type harmonics to flow into the shunt filter. Figure 4 introduces a typical series active filter suitable for simulating and designing purposes.

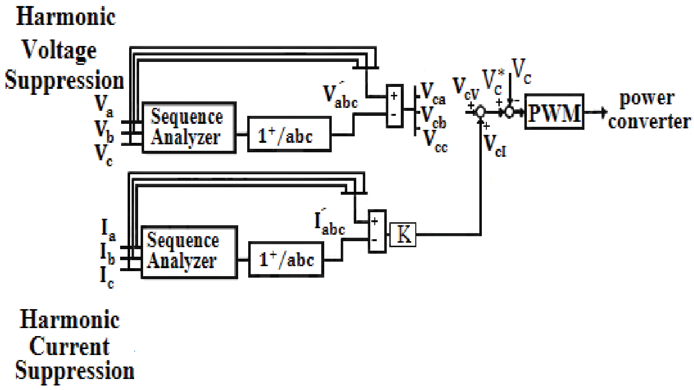

Figure 4. Single-phase series active filter controller block diagram

In the harmonic voltage suppression loop, the fundamental component of line voltage is extracted from the measured source voltage to mitigate voltage deficiencies. The main current harmonics are obtained by subtracting the positive fundamental current component from the measured source-end currents. The output voltage of the converter for harmonic current suppression is obtained from the multiplication of the calculated mains harmonic current and the equivalent harmonic resistor (K). A hysteresis voltage comparator is used to track the voltage command v^*_c to generate a proper PWM waveform to trigger the power switches of converter.

• **Shunt filter**: The shunt active power filters are used to eliminate load-terminal current harmonics and lead to having purely sinusoidal source-end currents. The control block diagram of general SAPF is shown in fig.5. A hysteresis current comparator is used to track the current command to generate a proper PWM waveform to trigger the power switches of converter.

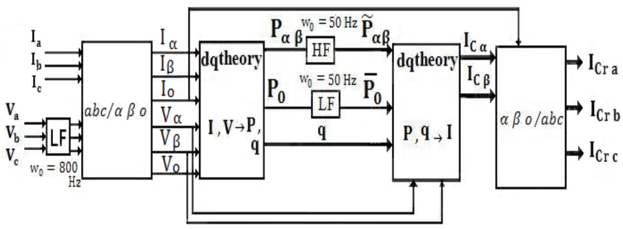

Figure 5. General Shunt active filter controller block diagram

The generalized theory of instantaneous power definition (GTIP) usually is used for reference signal determination in control schemes for both shunt and series active filtering. Due to the fact that UPQC has a limited power factor compensation capability [5], an independent converter is used to regulate DC-link voltage by an isolated control circuit as shown in Fig. 6.

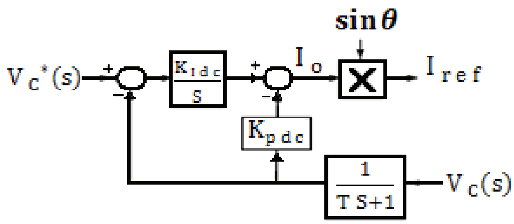

Figure 6. Control of active rectifier

This independent converter leads to activating algorithm simplicity and decreasing the element's power density. The universal power quality conditioning system (UPQS) is shown in fig.7.

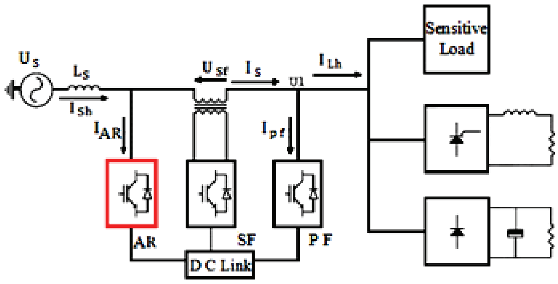

Figure 7. Universal power quality conditioning system (UPQS)

Active rectifier and shunt filter have a three phase voltage source topology, while the series filter has a three-phase four-wire topology. These forms of compensators are practically true for three-phase systems as long as load-terminal voltages remain balanced and sinusoidal. Nevertheless, for a three-phase four-wire system, when the power system is unbalanced and distorted, these unified compensators introduce unsatisfactory cancellation of the source zero sequence current and harmonics suppression. Moreover, the independent DC-link three-phase converter of UPQS at the source side, although, removes the limitation of power factor compensation capability, it leads to source-end current distortions and harmonics.

IV. Advanced Universal Power Quality Conditioning System (A-UPQS)

Let us suppose that v(*t*) involves all sequences (v (*t*) = v+ (*t*) + v− (*t*) + v^0 (*t*), where v+ (*t*), $v^-(t)$ and v^0 (*t*) respectively indicate positive, negative and zero sequences of v(*t*)) [6]. Therefore, the source-end currents, using the OS [8, 9], can be rewritten as:

$$(5)\quad \begin{cases} i_s(t) = i_s^+(t) + i_s^-(t) + i_s^0(t) \\ i_s^+(t) = \lambda \cdot v^+(t) \\ i_s^-(t) = \lambda \cdot v^-(t) \\ i_s^0(t) = \lambda \cdot v^0(t) \\ \lambda = \dfrac{\bar{P}(t)}{V(t).V(t)} \end{cases}$$

The compensation algorithm derived from the GTIP under both asymmetric and distorted three-phase load-terminal voltages provides unacceptable outcomes. The A-GTIP theory is proposed further solution to overcome these defects:

- One suggestion to overcome voltage asymmetry is to replace v(*t*) by v+(*t*) in (5). Hence, the new source-end currents and the shunt active injected currents are obtained as follows:

$$(6)\quad \begin{aligned} i_s(t) &= \frac{\bar{P}(t)}{V^+(t).V^+(t)} V^+(t) \\ i_c(t) &= i(t) - \frac{\bar{P}(t)}{V^+(t).V^+(t)} V^+(t) \end{aligned}$$

- As long as $V^+(t)$ doesn't include any harmonic components, the source-end currents remain purely sinusoidal. Otherwise, the non-sinusoidal $V^+(t)$ in the term v+ (*t*), v+ (*t*) acts as the source of distortion; therefore, the SAPF compensation algorithm will inject a distorted current. The new injected current of the shunt active filter would lead to a sinusoidal source-end currents in four-wire systems by v_1+ (*t*), defining as the fundamental component of v+ (*t*), as follow:

$$(7)\quad \begin{aligned} i_s(t) &= \frac{\bar{P}(t)}{V_1^+(t).V_1^+(t)} V_1^+(t) \\ i_c(t) &= i(t) - \frac{\bar{P}(t)}{V_1^+(t).V_1^+(t)} V_1^+(t) \end{aligned}$$

The proposed shunt active filter controller block diagram is shown in fig.8.

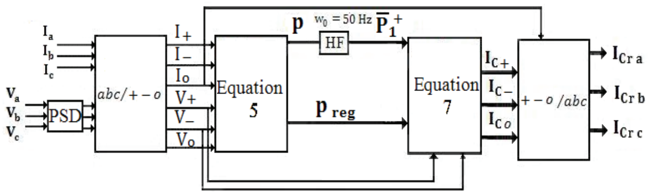

Figure 8. Proposed compensation algorithm (based on A-GTIP theory) block diagram

If a compensation algorithm is derived based on the Advanced GTIP for controlling the active compensator, all the distorted-unbalanced load-terminal voltages can be eliminated. Now, the proposed A-UPQS produces satisfactory performance even under distorted and unbalanced load-terminal voltages in three-phase four-wire systems. Moreover, by connecting an independent single-phase converter at the load side, unlike the previous proposition of a three-phase converter at the source side, it would be able to regulate the DC-link without any distortion because the shunt part of the A-UPQS leads to nullifying the current distortions and harmonics, generated by independent dc bus converter. Fig 9 shows the proposed Advanced UPQS.

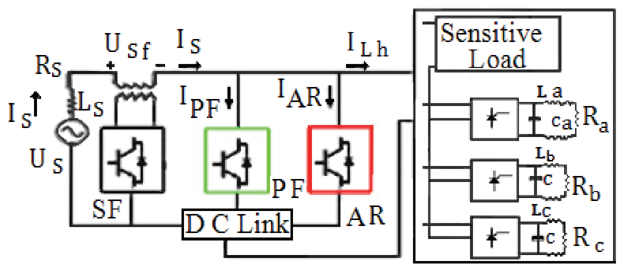

Figure 9. A-UPQS block diagram

V. Simulations and discussions

In this section, some simulations will be presented to verify the pliability of A-UPQS considering a micro-grid application. The simulated micro-grid that consists of a wind farm, synchronous generator as a power source, unbalanced non-linear load and advanced UPQS compensator is to be shown in Fig.10. This is a hypothetical situation; however, it is highly possible to occur in a practical micro-grid. The present simulation involves a 10 MW wind farm consisting of five wind turbines, a synchronous generator and the A-UPQS active filter (see fig.10, 11.) the detailed characteristics of which can be observed in tables1 and 2. It is assumed that the reactive power, produced by wind turbine, equals zero.

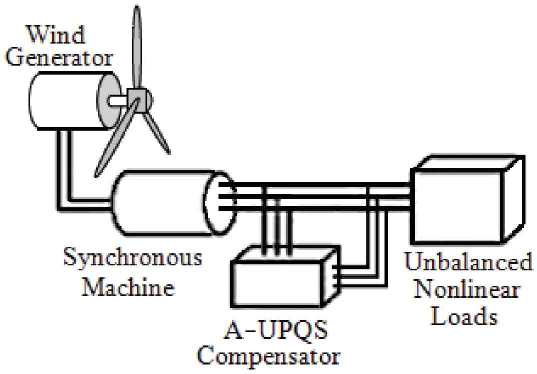

Figure 10. Simulated micro-grid involved nonlinear unbalanced load and Power Compensator

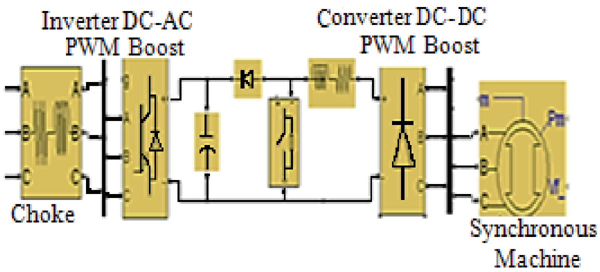

Figure 11.Synchronous generator block diagram in wind farm

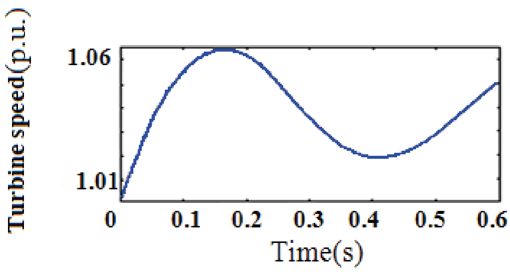

Figure 12. Velocity of Wind Turbines

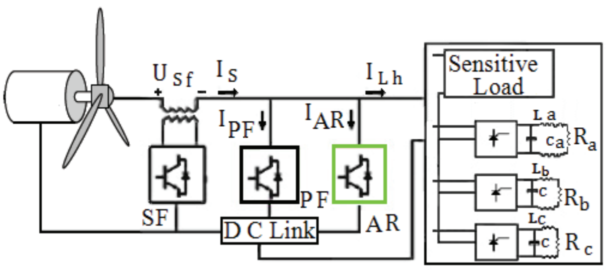

Figure13. A typical interconnection of the source, the load and the A-UPQS compensator

In this model a synchronous generator is connected to the distributed system through a rectifier, both boost PWM DC-DC converter and PWM DC-AC inverter use IGBT switches. The variable velocity of the wind turbine is normalized on the base of 11 m/s for duration of 0.6 second in per unit, as shown in fig.12. Also, the non-linear load of Fig.13 consists of three single-phase rectifiers that feed the following circuit elements:

$$\begin{cases} R_a = 10/3\ \ \Omega,\ \ L_a = 60e^{-2}H\ \ ,C_a = 0.3\ \ mF \\ R_a = 10\ \ \Omega,\ \ L_a = 60e^{-2}H\ \ ,C_a = 0.2\ \ mF \\ R_a = 10/3\ \ \Omega,\ \ L_a = 60e^{-2}H\ \ ,C_a = 0.3\ \ mF \end{cases}$$

A passive LCL-filter is used to attenuate the unwanted frequency components resulting from the switching modulation of shunt part of the A_UPQS. Parameters of the converter and the LCL-filter are tabulated in Table 3 [12].

In this simulation a hysteresis current control modulation technique is employed that drives the switches with variable frequencies [13]. Figures (a), (b) 14 respectively show the wind turbine three-phase voltages under distortion and system three-phase compensated voltages. Figures (a), (b) 15 show the source-end currents before and after the compensation by proposed A-UPQS in three-phase four-wire system, respectively. It can be seen that the distorted lines current will be perfectly eliminated.

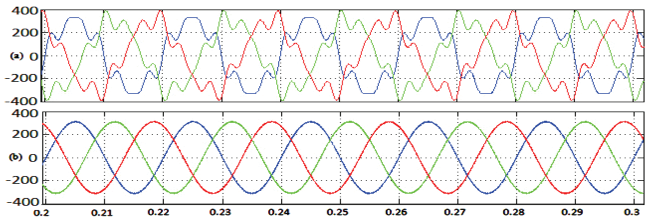

Figure 14.Simulation results: (a) wind turbine three-phase voltages (V) under distortion (THD 19.08%)., (b) system three-phase voltages (V) after compensation by A-UPQS (THD 0.47%).

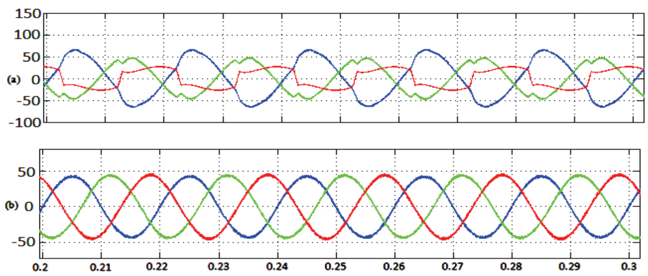

Figure 15. Simulation results: (a) the Load-terminal currents after compensation (A) (THD 34.03%), (b) the source-end currents after compensation in three-phase four-wire system by A-UPQS (THD 1.46%)

VI. Conclusion

This paper analyzes the characteristics of the general unified compensators which are utilized for eliminating the malfunctions of shunt active filters in three-phase three-wire systems. Mathematical analysis is presented to show that both p-q and p-q-r theories are unable to fully compensate the unbalance components as well as distortions. Hence, a compensation algorithm is developed based on the A-GTIP for the shunt device of the advanced universal power quality conditioning system. Further, a single-phase converter, connected to the load-side, regulates the DC bus of the advanced UPQS. This enables the A-UPQS to suppress the disturbances of previously suggested three-phase converter at the source-end. Thus, the proposed A-UPQS is able to fully cancel the source-end zero sequence current under any distorted unbalance conditions occur in a four-wire system. In brief, the A-UPQS produces a pure sinusoidal current at the source-end, increasing the efficiency and effectiveness of the power system. Simulation is used to confirm the stated improvements.

Table.1: synchronous generator parameters

parameter	value
Available power	2 MW
voltage	575 V
poles	2
Power factor	0.9
Inertia	0.62 Sec.
Stator Impedance (p.u.)	0.006
Stator Reactance (p.u.)	1.485

Table.2: wind farm parameters

parameter	value
Number	5
Shaft damping coefficient(p.u)	80.27
Inertia coefficient	4.32 Sec.

Table.3 the parameters of switching compensator

SAPF side LCL filter inductance L_1	4.1[mH]
Grid side LCL filter inductance L_2	0.5[mH]
LCL filter capacitor C_f	10 [µH]
LCL filter damping resistor R_f	20 [Ω]
SAPF Switching frequency	6:9[kHz]
SAPF DC-link capacitors (each one)	2 [mF]
SAPF DC-link voltage	700 [v]

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