Study of Distribution System Unified Conditioner (DS-UniCon)

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Abstract- In this paper, the concept, the proposed scheme and the model of DS-UniCon will be described with simulation results to show its validity. The discussion of power flow of DS-UniCon will be included to indicate its ability to ensure the power quality, reliability, power stabilizer and power flow control/management of power network as well as the Electric Vehicle charger station at the same time. The proposed FACTS's device, Distribution System Unified Conditioner (DS-UniCon), is a unified approach for all the existing compensators in FACTS's devices. It may be installed inside the distribution networks with the insurance of power quality and reliability as well as the power storage control function for Electric Vehicle Charger. By the way, the structure of this DS-UniCon model may be considered to form as a unified device to install at the interface between transmission side and distribution site to control the power flow and power quality. The economic comparison and power management of new concept of FRIENDS are also discussed with DS-UniCon.

Key words: Power Quality, Reliability, UPFC, UPS, UPQC, FACTS

1. Introduction

Recently, the concept of the custom power device [1] has been becoming more and more attention to the researchers for the power quality and reliability improvement. The development of custom devices has introduced emerging branches of technology such as Dynamic Voltage Restorer (DVR), Active Filter (AF) and Universal Power Flow Controller (UPFC) etc. Since the introduction of the Flexible AC Transmission System (FACTS) concept in 1990 [3] [4], the technology has been moving ahead at an increasing pace. The advanced control center technology, overall automation and the improved semiconductor switching devices represent a new era for transmission and distribution systems. However, up to now, there are many investigators to take different individual focal points on one of the below specialized aspects to reduce the custom power problems, e.g. harmonics, unbalance, reactive power compensation, power interruption, power system stability, voltage fluctuation and power quality management [5][6] etc.

Further increasing the reliability, improving the power quality and reducing the costs of power network are the main trends of the technology development of power system control and management. By the state-of-art of power electronics technology, the converging ways to improve the power quality and reliability are developed such as the Shunt Connected, Series Connected, and Combined Shunt and Series Connected Controllers/ Compensators. Table 1 lists all the existed FACTS's devices and the operational functions in power networks. For example, Static VAR Compensators (SVC) work for the reactive power compensation and voltage stabilizer so as to be a system oscillation damping device. Moreover, some specialized compensators have been utilized in power system for different manners. However, not only various problems shown in Table 1 to execute different FACTS's devices have the highly installation requirements and higher costs for users, but also expensive maintenance. Due to above considerations for improving power quality and the future trends of power system, the necessity to develop a new kind of unified conditioner in distribution networks.

This paper is to study the basic structure of Distribution Unified Conditioner (DS-UniCon) by a unified approach conditioner in order to fulfil all the power quality and reliability requirements as well as the large reservoir for storing energy due to the introduction of Electric Vehicles (EV) in last decades.

2. Conceptual Development of DS-UniCon

This application is to study and to acquire a unified conditioner for distribution system, which is called the Distribution System Unified Conditioner (DS-UniCon) and offers a higher effective and economic means to improve the power quality and reliability. The same structure of a unified approach FACTS's device as DS-UniCon may be installed at the interface between transmission side and distribution site with the insurance of power quality and reliability as well as the power flow control and EV charger. This device not only can compensate all the described problems in Table 1 but also has energy storage function at the same time. This energy storage function can reduce the peak load demand for the power generation and, when the power interruption happens in a specific area, this DS-UniCon can work as a Uninterruptible Power Supply to guarantee the power reliability. But in normal operation, it works as a harmonic damper, reactive power compensation, voltage regulator and system stablizer at the same time to ensure the power quality. By the way, DS-UniCon can work as the local electrical battery charger for future electrical vehicle charger station as well as the power quality and reliability station.

2.1 Requirements of DS-UniCon

Further analysis is taken from Table 1, the summary of power quality and reliability issues can be classified as follows:

- Current Quality
- Voltage Quality
- Reactive Power Control or Compensator
- Power Flow Control
- Frequency and Active Power Control
- Power Interruption

For the sake of future Electric Vehicles (EV), the battery charger is the addition requirement to the DS-UniCon.

- EV Battery Charger

It means that DS-UniCon should implement all the above-described functions at the same time.

2.2 Elements of DS-UniCon

Actually, DS-UniCon should have basically two functions such as the power quality compensation and energy storage. However, a unified approach device is taken so as to consider the functions of 3 independent FACTS's devices: Unified Power Quality Conditioner, Unified Power Flow Controller and Battery Energy Storage System/Uninterruptible Power Supply, shown in Figure 1 together in order to handle all the above described issues.

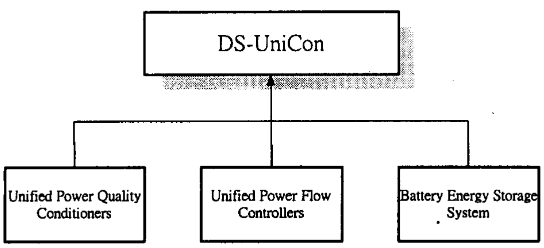

Figure 1

The main purpose of a UPQC is to compensate for voltage flicker/imbalance, reactive power, negative sequence current, and harmonics. In other word, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems [8][9]. The Unified Power Flow Controller is used to control the power flow through an electrical transmission line connecting various generators and loads at its sending and receiving ends and, actually UPFC are composed of STATCOM and SSSC [10][11]. The Battery Energy Storage System (BESS) can work for peak load supply, voltage regulation, load-frequency control, power interruption supply and electric vehicle charger station [12][13][14].

3. Basic Configuration of DS-UniCon

In this section, the proposed hardware and the model of DS-UniCon will be illustrated.

3.1 Proposed Scheme of DS-UniCon

The proposed basic configuration of DS-UniCon is shown in Figure 2. It is consisted of two shunt-connected converters and one series-connected converter with the dc-link capacitor and battery energy charger system in which may work as the Electric Vehicle Charger Station.

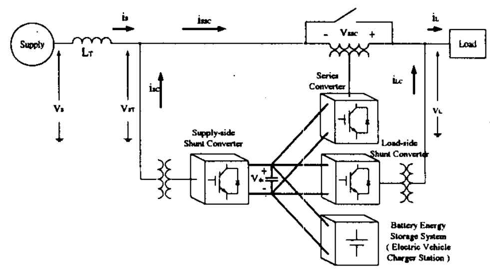

Figure 2

3.2 Modeling of DS-UniCon

The simplified model of DS-UniCon is shown in Figure 3. There are 2 current controlled sources, which represented the shunt-connected converters, and the series-connected converter is expressed by a voltage source. The Energy Pool can conceptually describe the Battery Storage Charger System due to the consideration of charging and discharging limitations of Lead-Acid batteries, however, the purpose of the dash-line connecting the Energy Pool with the v_{SSC} is to show that there is energy link between them conceptually.

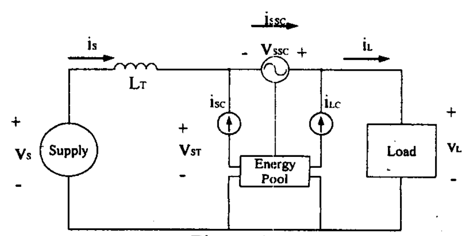

Figure 3

4. Power Flow Consideration of DS-UniCon

Instantaneous Real and Imaginary power is considered for analysis of instantaneous power flow in DS-UniCon for 3-phase power system. The instantaneous voltage and current in α,β and 0 frames can be transferred from a, b and c frames by the matrix [P], such as shown in (1) and (2).

$$\begin{bmatrix} v_0 \\ v_\alpha \\ v_\beta \end{bmatrix} = [P] \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} \qquad (1)$$

$$\begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} = [P] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \qquad (2)$$

, where $[P] = \sqrt{\frac{2}{3}} \begin{bmatrix} 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & \sqrt{3}/2 \end{bmatrix}$

Equation (3) show the instantaneous real power (p), instantaneous imaginary power (q) and instantaneous zero power (p_0).

$$\begin{bmatrix} p_0 \\ p \\ q \end{bmatrix} = \begin{bmatrix} v_0 & 0 & 0 \\ 0 & v_\alpha & v_\beta \\ 0 & -v_\beta & v_\alpha \end{bmatrix} \begin{bmatrix} i_0 \\ i_\alpha \\ i_\beta \end{bmatrix} \quad (3)$$

For the simplicity, the instantaneous zero power is ignored so as to consider 3-phase 3-wire system. Then, the instantaneous real power and instantaneous imaginary power can be divided with average part and alternative part as expressed in (4) and (5) respectively, and the average part can further divided into two parts: positive sequence active/reactive power and negative sequence active/reactive power [15]. They are composed of fundamental component and harmonic components with the same order of voltage and current components.

$$p = \bar{p} + \tilde{p} = \sum(\bar{p}_{n+,n+} + \bar{p}_{n-,n-}) + \tilde{p} \quad (4)$$

$$q = \bar{q} + \tilde{q} = \sum(\bar{q}_{n+,n+} + \bar{q}_{n-,n-}) + \tilde{q} \quad (5)$$

The average part of instantaneous real power and imaginary power are equivalent to active and reactive power respectively.

4.1 Operation of DS-UniCon as UPQC

The purpose of Unified Power Quality Conditioner (UPQC) is to compensate for voltage flicker/imbalance, reactive power, negative sequence current, and harmonics.

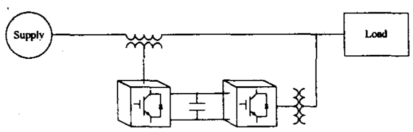

Figure 4

Figure 4 shows the general configuration of UPQC. The main purpose of the series-active filter is harmonic isolation between the sub-transmission system and a distribution system and has the capability of voltage flicker/imbalance compensation as well as voltage regulation and harmonic compensation at the utility-consumer point of common coupling. The main purpose of the shunt-active filter is to absorb current harmonics, compensate for reactive power and negative sequence current.

Considering the power flow of UPQC during compensation, oscillating parts of instantaneous real power and all parts of imaginary power do not require any active storage. But active power may be received by or, vice versa, released from the dc-link capacitor of UPQC for compensating the imbalance negative sequence of active power and harmonic power, checked by (4) and (5).

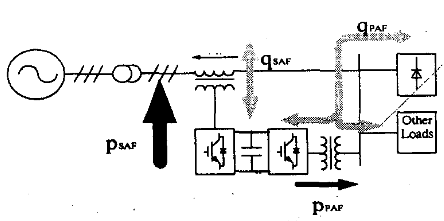

Figure 5

Figure 5 shows the instantaneous power flow in UPQC. However, the dc-link voltage v_c can be expressed as (6), where p_{SAF} and p_{PAF} are the absorbed or injected instantaneous active power which is composed of voltage flicker, imbalance and harmonics by the series-active filter and shunt active filter respectively so that the voltage of dc-link capacitor may fluctuate.

$$\tilde{v}_c = \frac{1}{C}\int \frac{\Delta p}{v_c} dt = \frac{1}{C}\int \frac{p_{SAF} + p_{PAF}}{v_c} dt \quad (6)$$

A very large dc-link capacitor can be used to reduce the voltage fluctuation or short-term compensation of imbalance active power and harmonic power can work well. But, it is not valuable for long-term compensation, as the capacitor needs to absorb or release the active power for a long time. By using the proposed configuration of DS-UniCon, the instantaneous power flow can be expressed graphically in Figure 6 so as to keep the dc-link voltage to be stable as well as the high quality of voltage regulation and battery storage for long-term operation as well as the transient state.

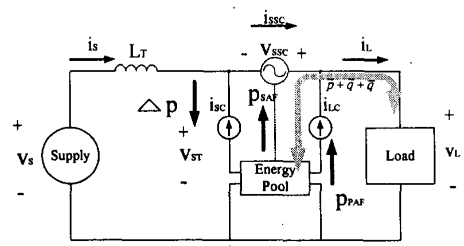

Figure 6

4.2 Operation of DS-UniCon as UPFC

The UPFC consists of two converters, which are connected through a common dc-link capacitor as shown in Figure 7. The shunt connected converter, known as STATCOM, injects an almost sinusoidal current with variable magnitude at the point of connection. The another converter connected in series, known as SSSC, injected almost sinusoidal voltage with variable amplitude and at any angle with respect to the line current to the transmission line. The exchanged real power at the terminals of one converter with the line flows to the terminals of the other converter through the common dc-link capacitor. In addition, each converter can exchange reactive power at its terminals independently.

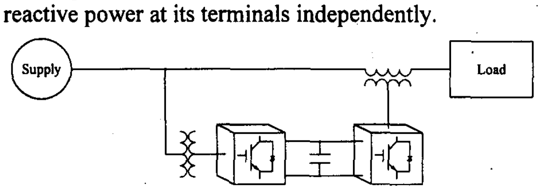

Figure 7

Figure 8 shows the instantaneous power flow of DS-UniCon operating as a UPFC in simplified model, in this mode of operation, the load side shunt connected converter of DS-UniCon does not need to take any action. However, the supply side shunt converter acts as the charger or discharge switch for energy pool as the real power can be absorbed or released from the series connected converter. Also, the series converter can act as the Dynamic Voltage

Restorer (DVR) as well as the power-flow controller according to the injected voltage amplitude and angle with respect to the line current.

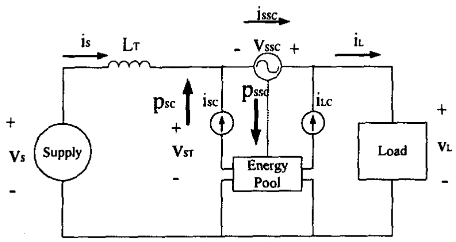

Figure 8

The (7) and (8) give the real and reactive power (P and Q) flow between the sending-end voltage source and the receiving-end voltage source.

$$P = \frac{V_S V_L}{X_{LT}} \sin(\delta_S - \delta_L) \qquad (7)$$

$$Q = \frac{V_S V_L}{X_{LT}} (1 - \cos(\delta_S - \delta_L)) \qquad (8)$$

When DS-UniCon is installed at the interface between the transmission site and distribution substation, it will include the UPFC function to control the power flow and the UPQC function to eliminate the harmonics, imbalance and reactive current in distribution site. However, when DS-UniCon is installed inside the distribution site, it does not need to havé UPFC function for transmission system but it needs to charge or discharge the battery and the function of UPQC.

4.3 Operation of DS-UniCon as BESS/UPS

The Battery Energy Storage System can work for peak load supply, voltage regulation of dc-link capacitor, load-frequency control, power interruption supply and electric vehicle charger station. In Figure 8, when $p_{SSC} > 0$, for active power compensation of harmonics and negative sequence power, and $p_{SC} = 0$, it works as the battery charger. However, vice versa, $p_{SSC} = 0$ and $p_{SC} > 0$, it works as the battery discharge. When the angular acceleration of generators is detected, $p_{SC} < 0$, the energy pool will absorb energy so as to be a positive damping system to make the system frequency stable. The supply side shunt converter can act as the peak load power supply, electric charger station, load-frequency controller as well as the voltage regulation. However, the series converter can perform as the voltage regulator and the voltage stabilizer during the operation as the uninterruptible power supply.

5. Operations of DS-UniCon

5.1 Operation Tasks of Converters in DS-UniCon

There are 2 shunt-connected and 1 series connected converters as shown in Figure 2 and their basic tasks of each individual converter are listed as follows.

Load-Side Shunt Connected Converter

- ♦ Current Harmonics Compensation
- ♦ Reactive Power Compensation
- ♦ Imbalance Current Compensation

Series Connected Converter

- ♦ Voltage Harmonics Compensation
- ♦ Voltage Imbalance Compensation
- ♦ Voltage Fluctuation/Flicker Compensation
- ♦ Active and Reactive Power Control with the Operation of Supply-Side Shunt Converter
- ♦ Voltage Stabilizer
- ♦ Uninterruptible Power Supply for Stable Voltage

Supply-Side Shunt Connected Converter

- ♦ Peak Load Supply
- ♦ Frequency Stabilizer
- ♦ Active and Reactive Power Control with the Operation of Series Converter
- ♦ DC-Link Voltage Regulator
- ♦ Active Power Supply Path for Compensation of Active Harmonic Power and Active Negative Sequence Power
- ♦ Battery Charger
- ♦ Over-charge and Over-discharge Protector Unit

The Series and Load-Side Shunt Converters need to generate the non-sinusoidal waveform to fulfil their operation targets, however, the Supply-Side Shunt Connected Converter needs to produce sinusoidal waveform only.

5.2 Economic Comparison

In this part, economic consideration of DS-UniCon is performed and compared with the devices that performed all the functions that DS-UniCon can do simultaneously. However, the actual cost is not counted out but the numbers of converters, transformers, capacitors and batteries are counted. Table 2 shows the summary.

	AF	DVR	UPS	UPFC	**Total**	**DS-UniCon**
Converter	1	1	1	2	**5**	**3**
Transformer	1	1	1	2	**5**	**3**
Capacitors	1	1	0	1	**3**	**1**
Batteries	0	0	1	0	**1**	**1**
Controllers	1	1	1	1	**4**	**1**

Table 2

It is obvious that it will be cheaper to perform all the functions simultaneously by using DS-UniCon than that by different individual devices together.

5.3 Power Management, FRIENDS and DS-UniCon

In [16], the new concept of **F**lexible **R**eliable and **I**ntelligent **E**lectrical E**N**ergy **D**elivery **S**ystem **(FRIENDS)** is proposed. The purpose of FRIENDS is to develop a desirable structure for future power delivery systems where small scale Dispersed-type Generators and Dispersed-type Energy Storage Systems are allocated near the demand side, and to develop reliable and energy conservation oriented operating strategies of the power systems. Figure 9 shows the general concept of FRIENDS. The FRIENDS should be expected to attain the following functions:

<1> Unbundled power quality services or multi-quality power supplies,
<2> Enhancement of flexibility in configuration of the power delivery systems,
<3> Maintenance of adequate reliability level in power supply,
<4> Load leveling and energy conservation,
<5> Demand side management,
<6> Enhancement of information service to customers.

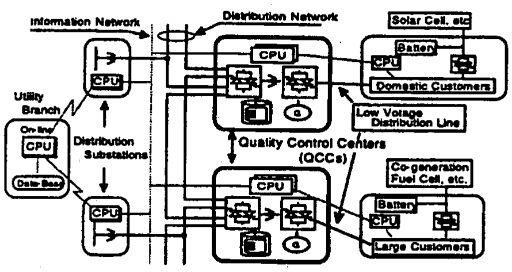

Figure 9

Figure 10 shows the distribution network of FRIENDS, Quality Control Centers (QCC) may be installed very closely to the power demand side, for example, at large/or middle scale industrial factories or buildings.

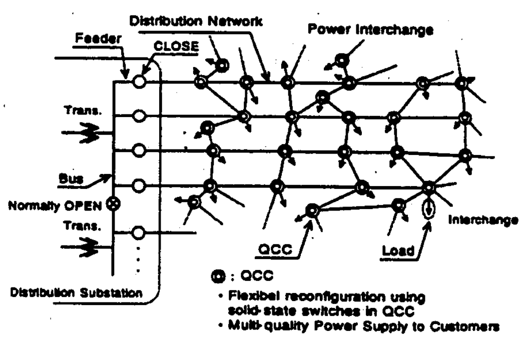

Figure 10

The unified approach device same as the structure of DS-UniCon can be the power flow control management system as well as the power quality enhanced system. In the concept of FRIENDS, it can be installed at the interface between the transmission site and distribution substation or in the distribution network as the QCC to manage the power flow, and can perform all the requirements of FRIENDS except the last point <6>.

6. Simulation Results

In this section, simulation results will be examined for the basic scheme of DS-UniCon and compensation of reactive current, harmonics and imbalance simultaneously by MATLAB/ SIMULINK.

The dynamic compensation and the energy releasing from the battery are performed. The energy releasing from battery of DS-UniCon can be considered as the peak-load power supply or system frequency stabilizer. In Figure 11, the DS-UniCon does not take any action until t=0.015 s. The compensation is achieved from t=0.015 s for enhancement of voltage quality and current quality. The peak-load power supply is performed at t = 0.06 s. From the simulation results, the power supply by the generator is reduced and it does not reduce the level of voltage quality and the current quality during compensation.

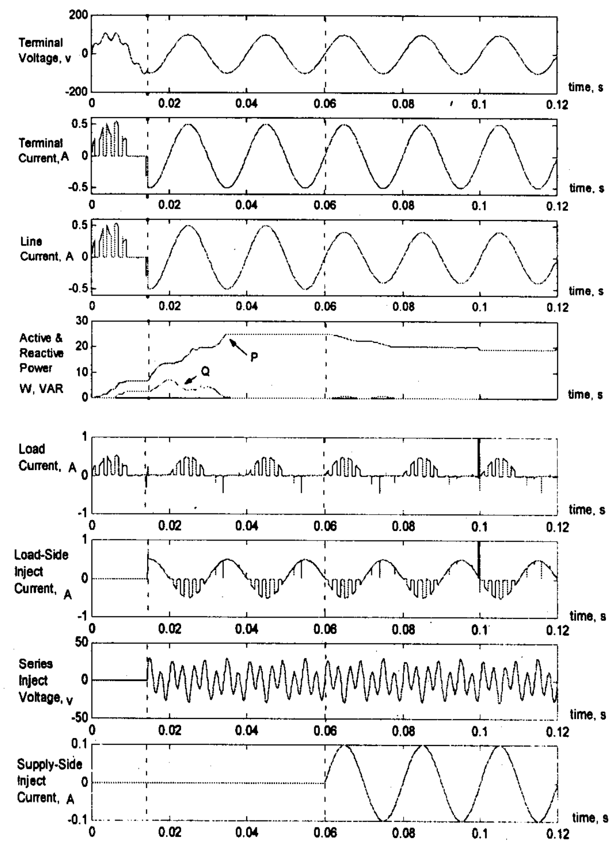

Figure 11

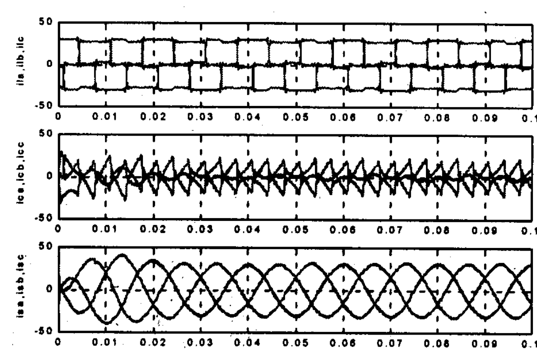

Figure 12

Figure 12 shows the achievement of DS-UniCon for reactive current, harmonics and imbalance compensation simultaneously.

7. Conclusions

The concept of DS-UniCon is proposed. The basic-configuration of DS-UniCon, model of DS-UniCon and individual tasks of converters of DS-UniCon is discussed with verification of simulation results by MATLAB/SIMULINK. The structure of DS-UniCon can ensure the power quality and reliability as well as the power flow control function and Electric Vehicle Charger. The economic comparison and the role of DS-UniCon in **F**lexible **R**eliable and **I**ntelligent **E**lectrical **EN**ergy **D**elivery **S**ystem (FRIENDS) are investigated. The DS-UniCon can perform the reactive power compensation, harmonic compensation, imbalance compensation, peak load power supply, uninterruptible power supply, voltage flicker/fluctuation compensator, power system stabilizer, and EV charger simultaneously. Actually, it is a new unified approach conditioner for FACTS.

8. References

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		Shunt Connected Compensators					Series Connected Compensators				Shunt & Series Connected Compensators		
		SVC	AF	STATCOM / SSC	SMES	BESS	TCSC	SSSC	DVR	UPS	UPQC	UAPLC	UPFC
Current Quality	Harmonics		**								*	*	
	Unbalance		*								*	*	
	Reactive I	*	*	*							*	*	
Voltage Quality	Harmonics										*	*	
	Unbalance								*		*	*	
	Fluctuation/Stability	*		*	*		*	*	**	*	*	*	*
	Flicker								*		*	*	
Power	Peak Load Supply				**	*				*			
	Power Interruption Supply					**				**			
	Reactive Power Compensation	**	*	**			*	*			*	*	*
	Active Power				*	*				*			
	Power Flow Control						*	**	*				**
Power System Stabilizer / System Oscillation Damping		*		*	*	*	*	*	*	*			*
Electric Vehicle Charger						*				*			
		S	N	S	S	S	S	S	N	S	N	N	S

Table 1

The symbol, *, means that the device has this function.
The symbol, **, means that this is the main function for this device.
The symbol, S, means that the device needs to generate sinusoidal waveform.
The symbol, N, means that the device needs non-sinusoidal waveform

SVC: Static VAR Compensators
AF: Active Filters
STATCOM/SSC: Static Synchronous Compensators
SMES: Super-conducting Magnetic Energy Storage
BESS: Battery Energy Storage System
TCSC: Thyristor Controlled Series Compensators
SSSC: Static Synchronous Series Compensators
DVR: Dynamic Voltage Restorers
UPS: Uninterruptible Power Supply
UPQC: Unified Power Quality Conditioners
UAPLC: Universal Active Power Line Conditioners
UPFC: Unified Power Flow Controller