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Electric Vehicle Charging Station with an Energy Storage Stage for Bipolar DC Bus

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ABSTRACT

This paper proposes a balancing approach for an electric vehicle bipolar dc charging station at the megawatt level, enabled by a grid-tied neutral point clamped converter. The work uses the presence of an energy storage stage with access to both of the dc buses to perform the complementary balance. This is aiming to reduce the hardware requirements of the system and maximize the usage of the ESS, whose main function is to perform the energy management related tasks. To meet this purpose, a three-level dc-dc interface is employed, allowing tocompensate the dc currents with a single ESS. In order to prevent the appearance of even-order harmonics in the input current during asymmetrical operation, an alternative switching sequence for the central converter is proposed. Results indicate that, without altering dramatically the charging process of the ESS, it is possible to cover the whole load scenario without the need of a balancing circuit. This allows the use of off-the-shelf products both for the rectifier and the fast chargers. In this paper, simulation and experimental results are presented to validate the proposed balancing strategy.

Keywords: Bipolar dc bus, electric vehicles, energy storage stage, fast charger, power balance management, three-level dc-dc converter.

I. INTRODUCTION

PLUG-IN ELECTRIC VEHICLESare considered under this category. Plug-in Hybrid Electric and BatteryElectric Vehicles, have emerged as the most probable successorfor conventional internal combustion engine vehicles. Despite of the increasing electricvehicle (EV) fleet, these vehicles still have to solve some shortcomingsbefore becoming a real alternative to transportation. The long recharging process of the batteries, limited mileagecapacity (typically below 200 km) and the lack of public fastcharging infrastructure are the main barriers to its widespread usage. To allow a large-scale penetration ofthis technology changes are required also from the grid pointof view, as the electricity demand will grow accordingly.

Nowadays, there is no real threat to the utility grid, as still the automotive industry is mainly sourced by the gasoline supply chain, but this will gradually will shift to a larger electricity consumption with transportation purposes, and if it is not addressed properly, the actual electric system will be unable to satisfy this demand.

In order to address the impacts of large-scale adoption of these vehicles in the utility systems, several studies have beencarried out, mostly based on the conventional slowcharging process of the batteries. This is mainly because,conventional charging is expected to remain as the preferredcharging method, and also the fast charging process ofthe EV batteries is still not a widespread practice amongthe owners, due to the lack of facilities and misconceptionsregarding the impact of this process to the battery pack.However, fast charging methods are still essential for a large-scaleadoption of EVs, as it will provide more flexibility to thedrivers, occasional longer trips addressing range anxiety. Additionally, in order to reduce power consumption fromthe utility grid during peak consumption hours, the presenceof ESS in these stations is gaining attention.

An alternative to enable fast charging is in the form of fastcharging stations, which refers to the concept of having high powerfast chargers installed off-board, similar to gas stationslocated in public places. The structure of these chargingstations can either be with an ac-bus, where each charging unitis fed by its independent ac-dc stage, or each unit connectedto a common dc bus enabled by a single ac-dc stage with higher power ratings. Currently, fast charging is onlyenabled by standalone units, each one with its independentrectifier stage using the ac-bus concept.

However, considering the dc nature of the loads, the commonDC-bus configuration appears as the viable solution, andalso presents advantages in terms of cost, efficiency and size,as fewer power conversion stages are needed.Moreover, this structure facilitates the integration of distributedgenerators or energy storage systems (ESS).

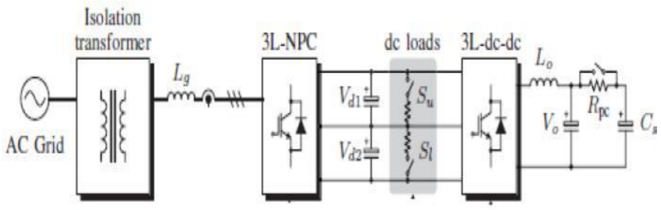

Figure 1.1 Proposed charging station architecture with balancing ESS

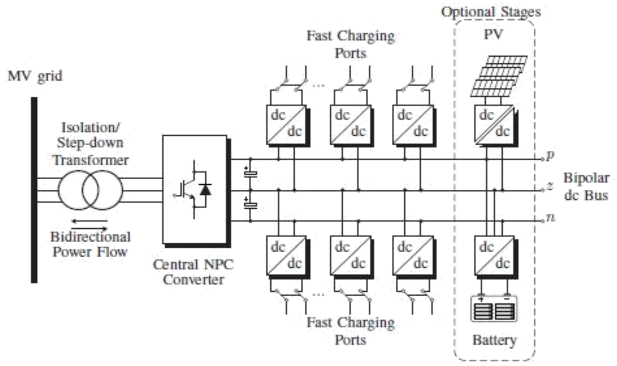

Figure 1.2 Proposed charging station architecture with balancing ESS

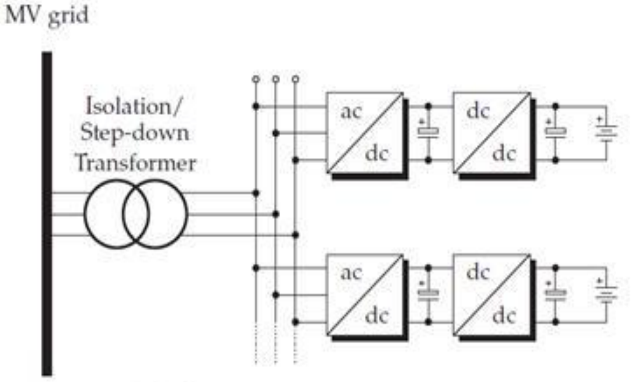

Figure 1.3 Common AC bus Charging Station architectures

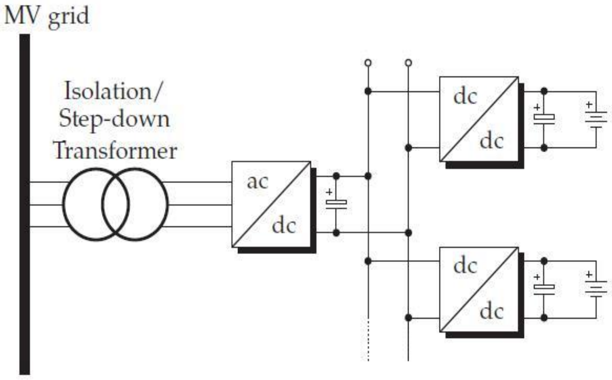

Figure 1.4 Common DC bus Charging Station architectures

II. THREE LEVEL NEUTRAL POINT CLAMPED CONVERTER/INVERTER

The diode-clamped inverter/converter was also called the neutral-point clamped (NPC) inverter because when it wasfirst used in a three-level inverter the mid-voltage level was defined as the neutral point level.A three-level diode-clamped inverter is shown in Figure 2.1 and Phase-A three-level diode-clamped inverter is shown in Figure 2.2.

Some of the important features of diode clamped inverter are given below:

Low voltage power semiconductor devices: The m-level diode clamped inverter requires (m+1) active devices(GTO and IGBT's etc.) per phase and each active device will see a blocking voltage of (Vdc / (m-1)).Duty cycle of switching devices: The duty cycle of the power switches is different. So switches of differentcurrent rating have to be used for optimal design.

(a) Rating for clamping diodes: For five and higher level inverters, the voltage blocking capability of thediodes are different. So the diodes will have different voltage ratings. Assuming that the characteristics ofdiodes are identical, then multiple diodes of same voltage rating have to be used to achieve requiredvoltage-blocking capacity. Hence, for asufficiently large number of levels, the number of diodes requiredwill become too large and will make the circuit less reliable. Also power circuit layout and packaging becomes difficult.

(b) Capacitor voltage unbalance: The midpoint voltage is derived using capacitors and these carry load current. Unequal loading of the capacitors leads to imbalance in the dc bus capacitor voltages and this will cause the dc mid pint voltage to drift. This is not a serious problem for utility applications such as, static VARgenerators (SVG), active power filters, etc., where the inverters need to supply only the reactive power.

(c) High voltage surge: During turn off, the devices will experience a high transient over voltage and alsosnubbers are required to distribute the voltage across clamping diodes in a uniform fashion. The design ofsnubbers is complicated, as the current through these snubbers is bi-directional.

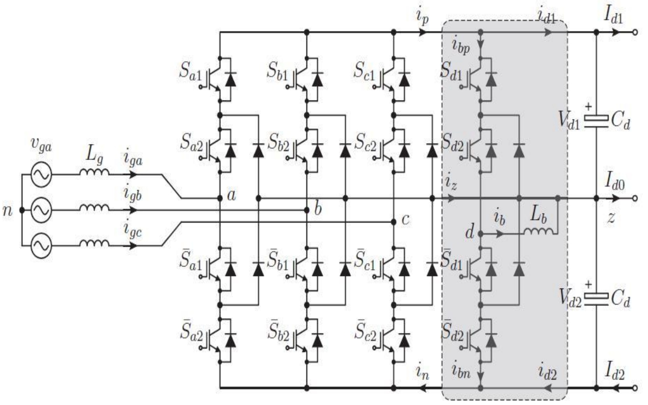

Figure 2.1 A three-level diode-clamped inverter(NPC)

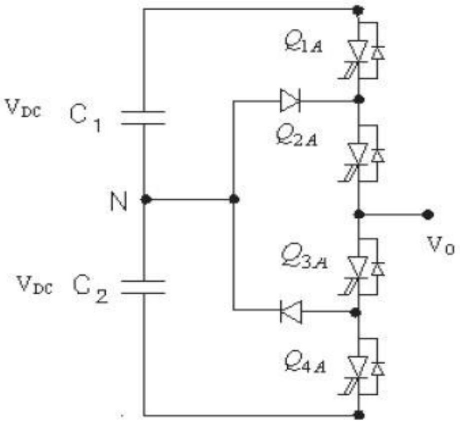

Figure 2.2 Phase-A three-level diode-clamped inverter (NPC)

Table 2. Switching sequence of the semi-conductor devices

Switches on	Switches off	Output voltage
Q1A, Q2A	Q3A, Q4A	+Vdc
Q2A, Q3A	Q1A, Q4A	0
Q3A, Q4A	Q1A, Q2A	-Vdc

A four leg three-phase NPC converter that acts as the grid interface is selected,because it offers superior harmonic performance and higher powerhandling capabilities. An additional leg is incorporated to act as abalancing circuit. The scaling of the system is thus made possible, which inturn allows the extension the power level if needed.According to the correct performance of the NPC is guaranteed onlywith the accurate control of its midpoint voltage. Hence, multiple solutionscan be found, which usually solve the problem inthe modulation stage with the implementation of a simple balancing mechanism.It is important to note that these schemes are mostly designed consideringthat the system is being used as a unipolar dc bus, either as a rectifieror in back-to-back configuration. Consequently they are not able to keep this voltage controlled under the bipolar structure. Therefore, a balancing techniquemust be developed. Then, the system provides a bipolar dc bus, andeach voltage feeds different loads. As such, unbalanced operation is inherentin the system, given the selected dc architecture and the nature of theintended application. This is explained as follows, as a result of the circulationof current through the neutral point of the converter the dc voltages maybecome unbalanced. Such circulation is imposed by the asymmetrical loadof the dc buses. This effect can be mitigated by alternating the connection ofthe loads to the dc buses. Nevertheless, even if this connection is promoted,unbalance operation still occurs because of the random arrival of the vehiclesto be charged, different battery characteristic, different charging powers,and so on. Therefore, despite the modulation stage performs the balancingcorrections to keep the voltage controlled, the unbalanced scenarios that thesystemis able to overcome.

III. THREE LEVEL DC-DC STAGE FOR ESS

As stated earlier, in order to perform the balancing complementto the grid-tied converter, the ESS must have accessto both dc buses. Considering this requirement, a threeleveldc-dc converter will be used as the dc-dc stage. Thischoice is further justified by the reduced voltage stress onthe switching devices, allowing the use of conventional lowvoltage-rated switches; improved output current waveform andimproved efficiency in comparison to conventional two-levelbased topologies. Finally, for this particular application,it will only require the inclusion of a single energy storagestage, as it will be able to compensate currents in both of thedc buses as it will be demonstrated.

The power circuit of the selected topology is presented in Figure 2.1, where it can be seen that can has three input terminals that can be directly connected to the bipolar charging station.The converter is composed of four switching devices alongwith their corresponding freewheeling diodes, the input filtercapacitors Cd1 and Cd2, and an output inductor Lo andcapacitor Co for filtering purposes.

Considering its structure, the basic requirement thatVd1 = Vd2

= Vd, and the valid combinations of its switchingsignals, the converter generates four voltage states, which areresumed in Table I. Each state results in a different equivalentcircuit, as presented in Figure 3. These states are depicted asfollows: when the switches Sk1 and Sk4 are turned on, theoutput voltage Vo is equal to the total input voltage 2Vd;then when Sk1 and Sk3 are on, Vo becomes Vd; the same output voltage is generated when the switches that are on are Sk2 and Sk4; finally, when the inner switches Sk2 andSk3 are turned on, the output voltage is equal to zero. Pleasenote that the switching states V1P and V1N generate opposite neutral-point currents, revealing the balancing capabilities ofthe converter. For the remainder of the paper, these states willbe denominated mid-states.

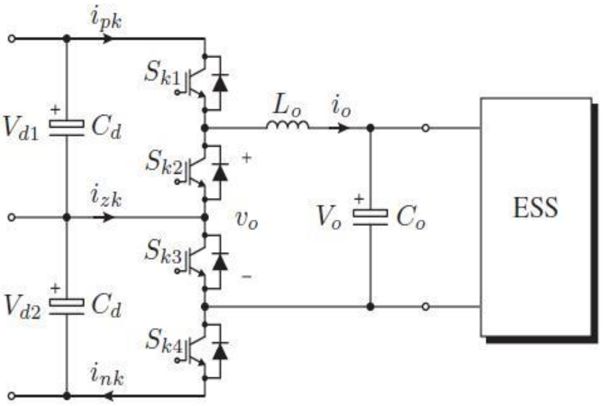

Figure 3.1 Circuit diagram for three-level dc-dc stage for ESS

Table 3. Switching sequence of semi-conductor devices

States	Switching State	Output Voltage	Neutral Current
V0	OO	0	izk = 0
V1P	PO	Vd1	izk < 0
V1N	ON	Vd2	izk > 0
V2	PN	2Vd	izk = 0

A. Operation Principle

From the circuit diagram in Figure 3.1, the operation of the outer switches Sk1 and Sk4 must be complementary to the inner switches Sk2 and Sk3, respectively, in order to avoid short-circuiting the input voltage sources. This means that the operation of the converter is regulated through two independent gating signals g1 and g4. The generation of these signals is usually done by the use of PWM modulators with phase shifted carriers. However, taking into account the generated switching sequence, it can also be synthesized by the single phase space vector modulation (SVM) approach.

The sequence will vary whether d ≤0.5 and d >0.5. Whereas, the duty cycle d is defined as usual, by the ratio between the output and input voltages, according to:

$$D= \frac{VO}{2Vi}$$

Where,

D= Duty Cycle
V0= output Voltage
Vi= Input Voltage

IV. SIMULATION CIRCUIT AND OUTPUT

The Simulation circuit for the electric vehicle charging station is shown in the below Figure 4.1.

Is important to highlight that despite the ESS converter is dramatically its operation, allowing to keep its main functionwhich is the charging and discharging of the energy bufferaccording to the selected energy management strategy. Furthermore,given the features of the three-level dc-dc converter,the minimal load condition does not impose a heavy restrictionon the ESS sizing, which means that its ratings are still setby the selected energy management approach. Experimentalresults using an ultra-capacitor stage have been carried out forthe validation of the method, but the concept can be extendedto different kinds of ESSs.Similar to the balancing method presented in, theproposed solution allows to keep high quality input signals,even under the presence of severe imbalances at the dc side.In addition, the alternate switching sequence allows to performthe complementary balancing while keeping the current freeof even-order harmonics.

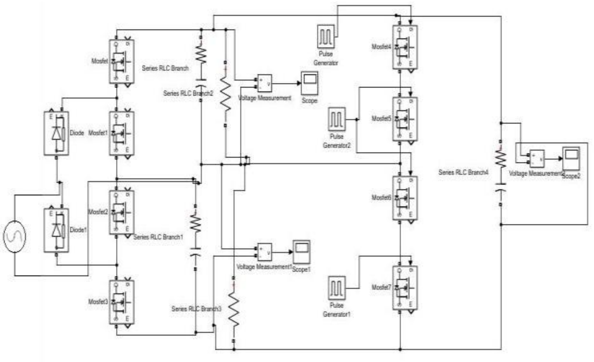

Figure 4. Simulation Circuit diagram forEV Station

Table 4. Expected Output as per Simulation Circuit
And Experimental Parameters

Parameter	Symbol	Value
Gird applied voltage	Vi	110V AC
Grid Frequency	Fg	50Hz
Output of the NPC Converter	Vd1	100V DC
	Vd2	100V DC
Input to 3Level DC-DC Converter	Vd	100+100V DC
Output of the 3Level DC-DC Converter	V0	200V DC

V. CONCLUSION

A different complementary balancing approach has beendeveloped and successfully validated, which takes advantagesfrom the optional stages that the distributed dc bus architecture allows. In this case, the presences of an energy storage stage, interfaced with a three-level dc-dc converter, allow the elimination of the balancing leg and provide the supplementarybalancing ability required. This leads to a reduction in theoverall cost of the charging architecture, as the requirementsfor the rectifier stage has been reduced, allowing to use off the-shelf equipment.

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