Controllable Electric Vehicle Fast Charging Approach Based on Multi-Stage Charging Current Methodology

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Abstract—This paper expresses a developed Electric Vehicle (EV) fast-charging control system based on multi-stage charging current methodology. The controller does not require a current sensor or any compensation circuit as in the current mode control (CMC) and the voltage mode control (VMC). The proposed controller drives the EV charging current to a predetermined value throughout an enhancement in the closed-loop feedback controller based on the duty cycle. A required duty cycle is anticipated through the design and analysis of the switched-mode DC-DC parasitic buck-boost converter supplied from Renewable Energy Sources (RESs) and has been represented as a variable DC supply. In this paper, the validity of the proposed controller has been studied by three main scenarios using the MATLAB/Simulink computer program. The scenarios proved the fast speed response and accuracy of the investigated controller.

Keywords—Electric Vehicles, Fast Charging, Lithium-ion battery, multi-stage charging current methodology, voltage mode controller, current-mode controller

I. INTRODUCTION

Electric vehicles (EVs) are surfacing as a transport mode free from carbon emissions and fossil fuel dependability [1]. Consequently, EVs turned into a part of the transportation electrification in smart cities[2]. Due to the exponential increase number of EVs, several charging methods have been developed to speed up the charging process and minimizing the energy loss of lithium-ion battery which considered as the backbone of EVs [3, 4]. The fast-charging methodologies have been categorized into the pulse charging technique, constant current-constant voltage technique (CCCV), and multi-stage charging current technique (MSCC) [3, 5]. The multi-stage charging current technique is based on charging the battery through multi-stage different currents with specific interval times. This technique proved its effectiveness as an optimized charging technique [5, 6].

Fast charging methodologies have been implemented in electric vehicle stations (EVSS) to solve the slow charging rate and queuing issue [7]. However, EVSSs are causing more stress and overloading to the power grid [8]. So, researchers were tending to implement fast-charging station based on the integration between the renewable energy sources (RESs) such as PV and wind energy systems and the utility grid [8, 9]. However, the intermittent and variable nature of RES still a challenge to power generation [10, 11].

The main component in charging the EV through the RESs (PV and wind) is the DC-DC converter. Over the past years, switched-mode DC-DC power converters such as (buck, boost, buck-boost, Flyback, etc) have been turned into an indispensable part in EVs [12]. Conventional buck-boost converters are widely used in almost all applications due to the capability for reducing the voltage level according to the corresponding input and output required voltages [13]. However, its voltage gain is limited due to the parasitic effect of the circuit elements. So many researchers carried out in-depth research, control methods through Pulse Width Modulation (PWM) especially in buck-boost converters to broaden high conversion ratios for both step-up/down modes, obtain high efficiency, constant frequency operation, simple controller and improve the dynamic response of the buck-boost converters [14, 15].

The most common closed-loop control methods have been implemented on the buck-boost power converters can be categorized into linear control design (LDC), sliding mode controller (SMC), voltage mode control (VMC), and current mode control (CMC) [16].

Linear control design (LDC) has been used based on the state-space averaging technique on the small-signal [17]. Due to its performance limitations for nonlinear feedback systems [18], researchers directed to nonlinear control methodologies. Sliding mode controller (SMC) is a nonlinear variable structure control based which targets a desired steady-state operation through tracking a certain reference path [19, 20]. However, a current sensor is needed in this category of controllers which considered as the main defect [20].

Voltage mode control (VMC) is a single loop controller-based where the output voltage is compared with a reference voltage with a compensator circuit to control the pulse width modulation (PWM) [21]. VMC has been renowned for its simple hardware implementation and flexibility [14]. Several controllers have been implemented in VMC such as compensator type III of boost converter [22], current ripple recovery of buck converter [21], adaptive passivity-based control of buck-boost converter [23], LQR output feedback integral control design of buck converter [24].

Current mode control (CMC) is considered as the standard methodology for output regulation and current control in high dynamic performance for DC-DC converters [16, 25]. CMC is based on dual current and voltage loops. Peak current-mode
control without slope compensation based on a general expression function of duty cycle and phase margin on buck converter has been declared in [26]. An efficient charge/discharge process of energy storage of a bidirectional buck-boost converter has been elaborated using CMC in [27]. A microcontroller of boost converter has been used to generate a controlled voltage injected into the compensation pin of CMC to tune the inductor current in [28]. A Digital peak current control technique ensured higher stability than the digital voltage-mode control method however the fluctuation of the input voltage in [29]. One of the main drawbacks of CMC is the dependency of a current sensor and a latching circuit based on a clocking signal[16].

This paper investigates a controllable EV fast-charging methodology based on the multi-stage charging current method. A switched-mode DC-DC parasitic buck-boost converter with a closed-loop feedback controller has been investigated. The stability of the charging current is implemented by enhancing the duty cycle of the proposed converter, however the fluctuation of the input voltage and the dynamic behaviour of the lithium-ion battery, the proposed controller does not need any compensation circuit or current sensor. It only requires the predetermined charging current and the initial measured voltage of the battery.

II. DC-DC BUCK-BOOST CONVERTER ANALYSIS

A. Parasitic Circuit of DC-DC Buck-Boost Converter

The analysis and design of the ideal buck-boost converter have been investigated early to avoid tedious calculations and experimental coincide with the elements. Nevertheless, researchers still using the non-parasitic buck-boost converters because of the simplicity and ideality of the components such as the diode, MOSFET, inductor, capacitor, and source. In this paper, the operation of the buck-boost converter in continuous conduction mode (CCM) has been used.

The study of the practical buck-boost converter is substantial where the output voltage is always less than the voltage of the ideal converter due to the internal resistance of each component and the extreme high-speed switching operation[18]. In Fig. 1, the elements of the converter with its parasitic resistances are represented as input voltage ($V_{in}$), the internal resistance of the source ($r_{in}$), switch resistance ($r_{sw}$), inductor ($L$), inductor resistance ($r_{L}$), capacitor ($C$), capacitor resistance ($r_{C}$), diode forward voltage drop ($V_d$), diode resistance ($r_d$) and the output resistance ($r_o$). The switching operation of the non-ideal converter during the ON-time and OFF-time operation in CCM has been presented in Fig. 1 (b) and Fig. 1 (c).

The output voltage of the DC-DC buck-boost converter for both ideal and practical has been investigated by varying the output resistance and input voltage corresponding to the duty cycle as shown in Fig. 2. It is observed that in Fig.2 (a) the output voltage is very close for both $r_o = 20 \Omega$ and $r_o = 50 \Omega$ so in this paper the output resistance has been considered as $20 \Omega$ to increase the efficiency by reducing the power loss in the charging process.

B. Duty Cycle analysis

The duty cycle of the buck-boost converter is the substantial parameter of controlling the output voltage. The maximum permitted duty cycle of the proposed practical converter can be calculated as in (1) [12].

![Fig. 1. DC-DC buck-boost converter with ON/OFF operation (a) Parasitic DC-DC buck-boost converter, (b) ON interval time equivalent circuit and (c) OFF interval time equivalent circuit](image1)

![Fig. 2. The output voltage of the buck-boost converter corresponding to the duty cycle (a) For various output resistances, (b) for various input voltages.](image2)
where
\[ a_1 = (r_o + r_e) (V_m + V_d) \]
\[ a_2 = r_o (r_o + r_e) (V_m + 2V_d) \]
\[ a_3 = -r_o (r_o + r_e) V_d \]
\[ b_1 = r_o^2 \]
\[ b_2 = (r_{sw} + r_m - r_d - r_o) (r_o + r_e) - r_o^2 \]
\[ b_3 = (r_o + r_e) (r_o + r_i + r_d) \]

Hence, the quadratic equation of the desired output voltage can be represented in terms of (1 - D) as follow
\[
(1 - D)^2 (V_o + r_o + r_e) (V_m + V_d) \\
+ (1 - D) (-V_m r_o (r_o + r_e)) \\
+ V_o (r_d - r_m - r_{sw}) (r_o + r_e) \\
- (r_o r_e)) \\
+ V_o (r_m + r_{sw} + r_s) (r_o + r_e) \\
= 0
\]

This equation can be simplified as
\[ A = (V_o r_o^2 + r_o (r_o + r_e) (V_m + V_d)) \]
\[ B = (-V_m r_o (r_o + r_e)) \]
\[ C = V_o (r_d - r_m - r_{sw}) (r_o + r_e) - (r_o r_e) \\
+ V_o (r_m + r_{sw} + r_s) (r_o + r_e) \]

By using (3), (4) and (5), the required duty cycle based on the desired output voltage and considering all the parasitic resistances can be expressed as
\[ D_{D借用} = 1 - \frac{-B \pm \sqrt{B^2 - 4AC}}{2A} \]

III. MODELLING OF LITHIUM-ION BATTERY

Due to the dynamic behavior of lithium-ion battery, RC second-order transient equivalent circuit has been implemented to simulate the battery in [5, 30]. The equivalent model of the lithium-ion battery in Fig. 3, consists of the required charging current \( I_d \), ohmic internal resistance \( R_i \), electrochemical polarization resistance \( R_{e} \), electrochemical polarization capacitance \( C_{e} \), concentration polarization resistance \( R_{c} \), concentration polarization capacitance \( C_{c} \), and open-circuit voltage \( OCV \) which depends on the state of charge \( SOC \) of the battery. The lithium-ion battery used in this research is 13.4 Ah with a nominal voltage 2.26 V. The parameters of the battery under study have been presented in [31].

IV. SIMULATION AND RESULTS OF THE PROPOSED CONTROLLABLE SYSTEM

The proposed system constructs of variable DC supply can be represented by any RES, DC-DC parasitic buck-boost converter, controller, and lithium-ion battery as shown in Fig. 4. The controller is targeting the fast charging of the lithium-ion battery by implementing the MSCC method based on the Cuckoo Optimization Algorithm (COA) which has been investigated in our previous work in [5]. MSCC is implemented in this paper by controlling the duty cycle of the closed-loop feedback controller of the DC-DC parasitic buck-boost converter. The anticipated duty cycle is calculated by (6) to ensure the required charging voltage expressed as follow
\[
V_{c-o} = I_d r_0 + I_d (R_i + R_a + R_p) + OCV \]

where the internal parameters of the lithium-ion battery are varying for each SOC, so the initial SOC is considered as 20%. The limitations of the proposed controller have been calculated by (1) where the maximum duty cycle \( D_{max} = 0.8745 \) (accepted) and \( D_{max} = 1.1707 \) (not possible to realize). The input parameters of the controllers are the required charging current for the proposed stage, the input voltage from the RESs, and the voltage of the battery needs to be charged.

Due to the dynamic behavior of the battery, each state of charge (SOC) represents a different value of the internal parameters. It is assumed that the battery has 20% SOC and all the internal parameters of the system under study are presented in Table I.

The flow chart describes the process of the proposed controller is presented in Fig. 5.
TABLE I. PARAMETERS OF THE PROPOSED CONTROLLABLE SYSTEM

| Element                          | Value            |
|----------------------------------|------------------|
| Converter Source Resistance (r_C) | 0.33 Ω           |
| Inductor (L_C)                   | 10 mH/0.055 Ω   |
| Capacitor (C_C)                  | 470 μF/0.06 Ω   |
| Diode (V_D, r_D)                 | 1 V/0.03 Ω      |
| DC Chopper (MOSFET) (r_m)        | 0.036 Ω         |
| Switching frequency (f)          | 20 kHz          |
| Load resistance (r_L)            | 20 Ω            |
| PV Panel                         |                  |
| Rated maximum power              | 100W             |
| Rated current                    | 5.56 A           |
| Rated voltage                    | 18V              |
| Lithium-Ion Battery              |                  |
| SOC                              | 20%              |
| R_L                              | 0.001538 Ω      |
| R_D                              | 0.001846 Ω      |
| C_L                              | 812.015 F        |
| C_D                              | 0.000615 Ω      |
| OCV                              | 1866.865 F       |

In the second scenario, the RES output voltage assumed to be constant 17.8V while the five stages of the charging currents procedure set to be 2A, 1A, 1.8A, 0.5A, and 0.1A during the charging of the proposed lithium-ion battery as in Fig. 7 (b). It is observed that the maximum rising time of the predetermined charging currents is 40ms during the first two stages of charging (from 2A to 1A).

In the third scenario, a combination of the previous two scenarios has been applied to the system as declared in Fig. 7 (c). The five stages of the charging currents proposed in the second scenario have been achieved during the variation of the extracted voltage from the RES. It is noticed that the maximum rising time is 45ms however, the speed-changing of the input voltage.

It is observed that the proposed three scenarios ensure the smooth fast charging approach response based on multi-stage charging current methodology. Furthermore, the controller behaviour is adapting with the dynamic behaviour of the lithium-ion battery and the variability of the RESs which reflects on varying the input voltage of the system during the charging process.

CONCLUSION

This paper proposes a fast-charging controller approach by applying the multi-stage charging currents methodology on the lithium-ion battery. The battery has been represented by RC second-order transient equivalent circuit. Three main scenarios have been implemented to study the dynamic behaviour of the system during the charging process. The first scenario studied the effect of the voltage variability of the RES due to the partial shading or variable wind speed on the regulation of the required charging current. The second scenario investigated five stages of charging currents while the input voltage from the RESs is considered as constant. The third scenario declared the validity of applying the MSCC methodology during the variation of the input voltage, charging currents and the internal parameters of the battery which varies for each SOC.

The scenarios proved the fast speed response and accuracy of the investigated controller through computer simulation using MATLAB/Simulink program.

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Fig. 6. The simulation of the proposed controller by MATLAB/Simulink program

Fig. 7. The relationship between the input voltage, charging current and lithium-ion battery voltage corresponding to the time during fast charging of (a) the first scenario, (b) the second scenario and (c) the third scenario.
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