Passivity-Based PI Control for AGVs Wireless Power Transfer System

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Abstract: Automatic guided vehicles (AGVs) recently have gained increasing attentions and applications, however, frequently stopping to recharge largely reduces service efficiency. Wireless power transfer (WPT) is considered as a practice energization way to solve this problem. In this paper, a passivity-based controller (PBC) and parameter designing method for compensation topology are proposed for AGVs WPT system. The PBC based on port-controlled Hamiltonian system (PCHS) is designed to achieve desired constant systematic working power by regulating the output voltage of DC/DC converter. The LCC-LCC resonant network is analyzed in the principle of the impedance matching method, and a proportional integral (PI) controller is implemented to realize zero steady-state error. Simulation are carried out in PLECS to verify analysis, and results show that proposed controller scheme and compensation designing method ensure the stability of the charging system against load variations, and the fast response performance of the control algorithm is also validated.

Keywords: Automatic guided vehicles (AGVs), wireless power transfer (WPT), impedance matching method, DC/DC converter, passivity-based control (PBC).

1. INTRODUCTION

Automatic guided vehicles (AGVs), also referred to as mobile robot with guidance device and motor control system, have been rapidly development in logistics industry Lu (2019). Stopping for charging reduces a lot of effective working time, resulting in low utilization rate and high use cost. With flexible charging position, safety and good adaptability, wireless power transfer (WPT) has drawn the attention of researchers RamRakhyani (2010); Zhang (2018) and it is meaningful to apply wireless charging to AGVs Lu (2019).

The compensation network is composed of loosely coupled transformer and external passive inductors or capacitors, which is the most important part in the design of a wireless charging system. According to the different series and parallel combination, there are four basic resonant compensation networks, i.e., series-series (SS), series-parallel (SP), parallel-series (PS) and parallel-parallel (PP) Zhang (2018); Feng (2016). In order to achieve a higher design degree, more higher order compensation network with more compensation elements is introduced. With current source characteristic and high efficiency, the LCC-LCC resonant compensation network is the most popular compensation topology Feng (2016); Li (2014). In addition, with the changing state of charge (SOC), the internal resistor characteristics of onboard battery changes dynamically. In order to obtain a stable operation, the resonant state must be independent of the load conditions Xiao (2018). In this paper, the impedance matching method is introduced to design the network parameters and the transfer power of this network has been analysed.

Fig. 1(a) shows the structure of WPT system for AGVs, which consists of the primary side and the secondary side. Fig. 1(b) describes an universal application scenario.
side is installed on the AGV chassis to pick up energy Lu (2019). It starts to work when the AGV arrives and stops at the parking points to handle the preset task, then energy can be transferred from primary side to secondary side during the parking gap. When the task is completed, AGV arrives to the next stop. With the intermittent charging during the parking gap, the 24-hour intelligent working mode is achieved, which not only increases efficient working time with a high utilization rate, but also reduces onboard battery pack and initial cost Zhang (2018).

For the typical voltage of the onboard battery is 24 V, the charging current can reach 75 A with 1.8 kW transfer power. In order to improve the transfer power, full wave rectifier with a high frequency transformer is connected with the LCC-LCC compensation network to increase the output voltage of this resonant network, which is proportional to the transfer power. A DC-DC Boost converter is added to regulate the transfer power by regulate the output voltage, i.e., the input voltage of this resonant network, resulting in a high nonlinear and unknown load to this converter.

The control method for this system is the another significant aspect. A lot of researches have been done for the controller of DC/DC Boost converter. In these control algorithms, passivity-based control (PBC) as a non-linear control method, has been widely applied in power electronics including DC/DC Boost converter. Several researchers have applied PBCs to control the output voltage of boost converter Jeltsema (2004); Ortega (2004). Without consideration of the parasitic parameters, this controller cannot maintain robust with load variations. Taking the parasitic resistor into consideration, a output feedback controller is proposed to achieve desired output voltage against load uncertainty Son (2011). However, since this controller is extremely complex, the algorithm is not easy to be implemented. Due to the high nonlinear and unknown load, it is not easy to design an algorithm that is robust against variable load Zeng (2014). Without consideration of the uncertain parasitic resistors, this paper proposes a easily implemented passivity-based proportional integral (PI) controller. In another word, a complementary PI controller is designed and combined with PBC to eliminate the steady-state error when the load changes, resulting in a easy implemented and strong robust controller.

The compensation topology and control algorithm are the most significant and tough to design in the field of WPT systems. The contribution of this paper is to propose a parameter design method for compensation circuit based on impedance matching method, and a PBC scheme is also applied to wireless charging system. With the proposed parameter designing method and PBC, a stable resonance is achieved to ensure the stability of the AGVs wireless charging system. Moreover, a PI controller is presented to work with the PBC to eliminate the steady-state error against load variations.

This paper is organized as follows. In section 2, the analysis of the LCC-LCC compensation is studied, and the impedance matching method also can be obtained. The passivity-based PI controller is proposed in Section 3. The AGVs wireless charging system is presented in section 4, while some simulations are also carried out in PLECS. Finally, Section 5 presents the conclusions.

2. ANALYSIS ON THE LCC-LCC COMPENSATION NETWORK

2.1 LCC-LCC Compensation Network

As shown in Fig. 2, $L_1$ and $L_2$ are the primary coil and the secondary coil, and the alternating current (AC) equivalent resistors are $R_1$ and $R_2$, respectively. $L_{f1}$ and $C_{f1}$ are the primary resonant inductor and capacitor, respectively. $L_{f2}$ and $C_{f2}$ are the secondary resonant inductor and capacitor, respectively. $C_1$ and $C_2$ are the primary and the secondary compensation capacitors, respectively. $M$ is the mutual inductor between the two coils.

2.2 Impedance Matching for Two-Port Network

Due to mutual coupling, the LCC-LCC compensation network can be described as a two-port network. Suppose that the input voltage between the port $A - B$ is $U_{AB}$ and the output voltage between the port $a - b$ is $U_{ab}$. The current flowing through the primary coil and the secondary coil are $I_1$ and $I_2$. $I_{L1}$ and $I_{L2}$ represent the currents on $L_{f1}$ and $L_{f2}$. $\omega$ denotes the working angular frequency and the frequency is $f$. The two-port network can be expressed as

\[
[\begin{bmatrix} \dot{U}_{AB} \\ \dot{U}_{ab} \end{bmatrix}] = [\begin{bmatrix} Z_{11} & Z_{12} \\ Z_{21} & Z_{22} \end{bmatrix}] [\begin{bmatrix} I_{L1} \\ I_{L2} \end{bmatrix}]
\]  

where

\[
Z_{11} = j[H_{11} - (H_{21} - jR_2)/(\omega^2 C_{f1} H_3)]
\]

\[
Z_{21} = Z_{12} = j\omega M/(\omega^2 C_{f1} C_{f2} H_3)
\]

\[
Z_{22} = j[H_{22} - (H_{12} - jR_1)/(\omega^2 C_{f2} H_3)]
\]

\[
H_{11} = \omega L_1 - (\omega C_1)^{-1} - (\omega C_{f1})^{-1}
\]

\[
H_{12} = \omega L_{f1} - (\omega C_{f1})^{-1}
\]

\[
H_{22} = \omega L_2 - (\omega C_2)^{-1} - (\omega C_{f2})^{-1}
\]

\[
H_{21} = \omega L_{f2} - (\omega C_{f2})^{-1}
\]

\[
H_3 = (H_{21} - jR_2)(H_{12} - jR_1) - \omega^2 M^2
\]

The open-circuit and short-circuit method is introduced to solve the network parameters. When the $U_{ab}$ is applied on port $a - b$, the open-circuit voltage (OCV) can be derived as $\dot{U}_{AB} = U_{AB} |_{U_{ab}=0} = -\frac{Z_{22}}{Z_{12}} \dot{U}_{ab}$, and the short-circuit current (SCC) can be obtained as $\dot{I}_{Lf1SC} = \dot{I}_{Lf1} |_{U_{AB}=0} = -\frac{Z_{12}}{Z_{22}} \dot{U}_{ab}$. Then, the equivalent impedance $Z_{eq1}$ between port $A - B$ can be expressed as follows
Similarly, when the $\dot{U}_{AB}$ is applied on port $A - B$, we can derive that OCV is $\dot{U}_{abOC} = \dot{U}_{ab}|_{I_{L2} = 0} = \frac{Z_{22} \dot{U}_{AB}}{Z_{11}}$, and the short-circuit current (SCC) is $I_{L2SC} = \dot{I}_{L2} |_{U_{ab} = 0} = \frac{Z_{22} \dot{U}_{AB}}{Z_{11}}$. Then, we obtain the equivalent impedance $Z_{eq2}$ between port $a - b$

$$Z_{eq2} = \frac{\dot{U}_{abOC}}{I_{L2SC}} = \frac{Z_{12} - Z_{11} Z_{22}}{Z_{11}}$$

Substituting (2) into (4) and (5), respectively. We obtain

$$Z_{eq1} = \frac{\omega^2 M^2}{\omega^2 C_f^2 H_3 \left[ R_1 - j(\omega^2 C_f^2 H_4 H_22 - H_{12}) \right] - j(H_{12} - \frac{H_21}{\omega^2 C_f^2 H_3})}$$

$$Z_{eq2} = \frac{\omega^2 M^2}{\omega^2 C_f^2 H_3 \left[ R_2 - j(\omega^2 C_f^2 H_4 H_{11} - H_{21}) \right] - j(H_{21} - \frac{H_12}{\omega^2 C_f^2 H_3})}$$

When the two-port network operates in the resonant state, the input and output equivalent impedance of this network must be the smallest. Thus, the maximum transfer power and the maximum transfer efficient can be achieved. According to the resonance theorem, the imaginary part of the input and output impedances should be 0, i.e., $Im(Z_{eq1}) = Im(Z_{eq2}) = 0$. Then, from (6) and (7), we get

$$H_{11} = H_{12} = H_{22} = H_{21} = 0$$

Combining (3) with (8) yields the resonant condition

$$\begin{cases}
\omega L_1 - (\omega C_1)^{-1} - (\omega C_f)^{-1} = 0 \\
\omega L_2 - (\omega C_2)^{-1} - (\omega C_f)^{-1} = 0 \\
\omega L_f - (\omega C_f)^{-1} = 0
\end{cases}\quad(9)$$

With the impedance matching method, a stable resonance is easy to be achieved according to (9). The resonant conditions of primary-side and secondary-side are only related to their own circuit parameters, which are independent of mutual inductor and output load.

### 2.3 Transfer Power of the Network

While $R_1$ and $R_2$ are too small to influence the system, in order to facilitate the analysis and design, the AC equivalent resistors are regarded as 0, i.e., $R_1 = R_2 = 0$.

When the LCC-LCC network is working in the resonant state, the series connection of resonant inductor and resonant capacitor on each side can be regarded as a low-pass filter, resulting in the attenuation of high frequency components. Therefore, fundamental frequency components of the voltage and current on the two coils play a dominant role, which can be regarded as sinusoidal wave.
where $i$ and $v$ represent, respectively, the input inductor current and the output voltage on capacitor; $E$ is the external input voltage; and $d$ represents the duty ratio of IGBT.

### 3.2 Passivity-Based Control

The dynamic system (13) can be written as a port-controlled hamiltonian (PCH) form as follows:

$$
\begin{align*}
\dot{x} &= [J(x) - R(x)] \cdot \frac{\partial H(x)}{\partial x} + \zeta + g(x)u \\
y &= g^T(x) \frac{\partial H(x)}{\partial x}
\end{align*}
$$

(14)

where $x \in R^n$ is the state vector; $J$, $R: R^n \rightarrow R^{n \times n}$ are the interconnection and dissipation matrices, respectively, with $J(x) = -JT(x)$ and $R(x) = RT(x)$; $H: R^n \rightarrow R$ is the total stored energy function; $g: R^n \rightarrow R^{n \times m}$ is the input matrices; $\zeta$ represents the external force; and $u, y \in R^m, m < n$, are the control action and the output function, respectively.

From the energy view point, the storage energy function of the dynamic system can be expressed as

$$
H(x) = \frac{1}{2} x^T Q x
$$

(15)

where $x = (x_1, x_2)^T = (L \cdot i, C \cdot v)^T$, $x_1$ and $x_2$ represent the inductance flux and the charge in the capacitance, $Q \in R^{n \times n}$ is a diagonal symmetric matrix representing the circuit parameters and $Q = \text{diag}(1/L, 1/C)$. Combining (13) with (14) we get

$$
J(x) = \left( \begin{array}{cc} 0 & -1 \\ 1 & 0 \end{array} \right), R(x) = \left( \begin{array}{cc} 0 & 0 \\ 0 & 1/R \end{array} \right), \zeta = (E, 0)^T, g(x) = \left( \begin{array}{c} x_2/C \\ -x_1/L \end{array} \right).
$$

In this paper, the expected energy function of system (14) can be written as (16), let $x^*$ is an admissible equilibrium point of $x$, and $\hat{x} := x - x^*$.

$$
H_0(x) = \frac{1}{2} \hat{x}^T Q \hat{x}
$$

(16)

Assume there are matrices $J_d(x) = -J_d^T(x)$, $R_d(x) = R_d^T(x)$, $x \in R^n$ and $H_d(x)$ is such that

$$
H^* := \arg \min H_0(x)
$$

Then, assume there exists $u = \beta(x)$, the closed-loop dynamic system (14) can be rewritten as follows

$$
\dot{x} = [J_d(x) - R_d(x)] \frac{\partial H_d(x)}{\partial x}
$$

(18)

with $x^*$ a stable equilibrium. According to La Salle’s invariant principle, if the largest invariant set under the closed-loop dynamics (18) contained in

$$
\{ x \in R^n | \frac{\partial H_d^T(x)}{\partial x} R_d \frac{\partial H_d(x)}{\partial x} = 0 \}
$$

(19)

equals $\{x^*\}$. Then, the closed-loop system is asymptotically stable.

**Proof.** Substituting $u = \beta(x)$ into (14) yields (18). Since $J_d(x)$ is negative-symmetric Matrix and $R_d(x)$ is positive-symmetric Matrix, the time derivative of the storage function is obtained

$$
\dot{H}_d(x) = - \left( \frac{\partial H_d(x)}{\partial x} \right)^T R_d \frac{\partial H_d(x)}{\partial x} \leq 0
$$

(20)

then, $x^*$ is a stable equilibrium point and $H_d(x)$ can be regarded as a Lyapunov function. Based on La Salle’s invariant principle and the conclusion (19), the dynamic system is proved to be asymptotically stable.

Combining (14) with (18), we have

$$
\begin{align*}
&[J_d(x) - R_d(x)] \frac{\partial H_d(x)}{\partial x} \\
&= [J(x) - R(x)] \frac{\partial H(x)}{\partial x} + \zeta + g(x)u
\end{align*}
$$

(21)

Assuming that $H_d(x) = H(x) + H_0(x), J_d(x) = J(x) + J_d(x), R_d(x) = R(x) + R_d(x), u = d$ is the duty ratio of the IGBT and $K(x) = \frac{\partial H_d(x)}{\partial x} = \frac{\partial H_d(x)}{\partial x} - \frac{\partial H(x)}{\partial x}$. Let $J_d(x) = 0, R_d(x) = \text{diag}(r_1, 1/r_2)$, where $r_1$ and $r_2$ are the injected virtual impedances. Then, (21) can be taken as follows

$$
\begin{align*}
&[J_d(x) - R_d(x)] \frac{\partial H_d(x)}{\partial x} \\
&= - [J(x) - R(x)] \frac{\partial H(x)}{\partial x} + \zeta + g(x)u
\end{align*}
$$

(22)

where

$$
J_d(x) = \left( \begin{array}{c} 0 \\ 0 \end{array} \right), \\
R_d(x) = \left( \begin{array}{c} r_1 \\
0 \\ 0 \\ 1/r_2 - 1/R \end{array} \right), \\
K(x) = \left( -x_1^*/L - x_2^*/C \right).
$$

Now, (22) can be further simplified, that is

$$
\begin{align*}
x_1 = \frac{r_1}{L} x_1 + \frac{1 - d}{C} x_2 + E \\
x_2 = \frac{1 - d}{L} x_1 + \frac{v}{r_2} C x_2 - \frac{1}{R C} x_2
\end{align*}
$$

(23)

Here, substituting $x_1, x_2$ into (23), we get

$$
\begin{align*}
&I^* r_1 = i \cdot r_1 + v(d - 1) + E \\
&V^* \frac{r_2}{r_2} = i(1 - d) + v \frac{v}{r_2} - \frac{v}{R}
\end{align*}
$$

(24)

(25)

where $V^*$ and $I^*$ are the expected steady-state values of $v$ and $i$, here, the duty ratio can be obtained

$$
\begin{align*}
d &= \frac{v - E + r_1 (I^* - i)}{v}
\end{align*}
$$

(26)

Assuming that the loss in the DC/DC converter is neglected, the relationship between the steady-state value of output voltage and the steady-state value of inductance current can be obtained law of conservation of energy, when the system reaches a stable state, that is

$$
I^* = \frac{V^*^2}{ER}
$$

(27)

Combining (27) with (28), the duty ratio becomes

$$
\begin{align*}
d &= \frac{v - E + r_1 (V^*^2/ER - i)}{v}
\end{align*}
$$

(28)
In order to simplify the modeling of DC/DC converter, the loss of IGBT, parasitic resistors of components and power loss caused by parasitic parameters have been neglected. Therefore, according to the law of energy conservation, the input power of the converter circuit equals its output power. However, the power loss mentioned above can not be neglected in practice. Due to the load variations and uncertainties of system parameters, the system can not be able to reach the desired output voltage without a steady-state error using (28). What's more, the load of the DC/DC converter, consists of several different and complex circuit modules, which cannot be just simplified as a resistor load $R$. Then, a PI controller is introduced and combined with the (26) to eliminate the steady-state error, resulting in a passivity-based PI controller. Fig. 4 shows the scheme of the controller for this system.

4. SIMULATION RESULTS

Simulations are carried out in PLECS to validate the proposed controller. Table 1 shows parameters of this system. The dynamical changed battery voltage with the SOC is simulated by the controlled voltage source. The control goal is to obtain desired charging power by regulating the output voltage of DC/DC converter with respect to the variable load condition. And a fair comparison test applied PID algorithm, which is referred as dual closed-loop PI control, is also implemented.

### Table 1. system parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary resonant inductor $L_{f1}$</td>
<td>47.10</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Secondary resonant inductor $L_{f2}$</td>
<td>46.81</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>primary resonant capacitor $C_{f1}$</td>
<td>74.44</td>
<td>nF</td>
</tr>
<tr>
<td>Secondary resonant capacitor $C_{f2}$</td>
<td>74.90</td>
<td>nF</td>
</tr>
<tr>
<td>Primary compensation capacitor $C_{1}$</td>
<td>97.95</td>
<td>nF</td>
</tr>
<tr>
<td>Secondary compensation capacitor $C_{2}$</td>
<td>101.74</td>
<td>nF</td>
</tr>
<tr>
<td>Primary coil $L_{1}$</td>
<td>82.90</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Secondary coil $L_{2}$</td>
<td>81.27</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Mutual inductor $M$</td>
<td>26.28</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Resonant frequency $f$</td>
<td>85</td>
<td>kHz</td>
</tr>
<tr>
<td>Battery voltage $U_b$</td>
<td>22 – 28</td>
<td>V</td>
</tr>
<tr>
<td>Switching frequency $f_s$</td>
<td>20</td>
<td>kHz</td>
</tr>
<tr>
<td>Capacitor of Boost $C$</td>
<td>400</td>
<td>$\mu$F</td>
</tr>
<tr>
<td>Inductor of Boost $L$</td>
<td>2500</td>
<td>$\mu$H</td>
</tr>
<tr>
<td>Parasitic resistor of $R_C$</td>
<td>10</td>
<td>$m\Omega$</td>
</tr>
<tr>
<td>Parasitic resistor of $R_L$</td>
<td>10</td>
<td>$m\Omega$</td>
</tr>
<tr>
<td>Nominal output voltage $V^*$</td>
<td>650</td>
<td>V</td>
</tr>
<tr>
<td>External input voltage $E$</td>
<td>310</td>
<td>V</td>
</tr>
</tbody>
</table>

In the simulation tests, this controlled voltage is step changed between 22V to 28V, which is the disgusting load variation. According to the variable battery voltage, we can identify three distinct modes: mode 1: the battery voltage is unchanged at 22V; mode 2: the voltage is step changed from 22V to 28V; mode 3: the voltage is step changed from 28V back to 22V.

Fig. 5 shows the simulation results applied dual closed-loop PI, with the inner loop $K_{p1} = 0.5$, $K_{i1} = 0.012$ and outer loop $K_{p2} = 0.04$, $K_{i2} = 0.001$. Due to the parasitic resistors in $L$ and $C$, the output voltage cannot be stable without a steady-state error. During these three modes, the stable output voltage are 652V, 651.8V and 652.5V, and the steady-state error are 2.0V, 1.8V and 2.5V. It indicates that steady-state error exists in all these modes, which increases with the variable load. From mode 1 to mode 2, the transient time is 15ms. The peak ripple voltage and current are 650.5V and 6.6A, respectively. From mode 2 to mode 3, the transient time is 15ms. The peak ripple voltage and current are 653.5V and 4.5A, respectively.

The simulation results using this proposed controller are shown in Fig. 6. The parameters of compensation PI are $K_p = 1.2$, $K_i = 0.055$ and the virtual impedance $r_1 = 25$. Due to the complementary effect, the stable output voltage in these three modes are 650V without steady-state error. From mode 1 to mode 2, the transient time is 5ms. The peak ripple voltage and current are 649.3V and 7.3A, respectively. From mode 2 to mode 3, the transient time is 5ms. The peak ripple voltage and current are 651.1V and 5A, respectively.

Simulation results show that the proposed controller has a much better response performance, and the transient time is three times less than that using dual closed-loop.
5. CONCLUSION

This paper has proposed a PBC and compensation designing method for AGVs WPT system. The proposed control has achieved desired systematic charging power by regulating the output voltage of DC/DC converter. With the principle of the impedance matching method, the LCC-LCC resonant network has been analyzed, then a stable resonance irrelevant with the mutual inductor and output load has been obtained. A PI controller has been designed to operate with PBC to eliminate the steady-state error. Simulation results have shown that the proposed control scheme and designing method not only can ensure the stability but also achieves desired response performance of the system.

REFERENCES