An Optimal PID Controller for a Bidirectional Inductive Power Transfer System Using Multiobjective Genetic Algorithm

Michael J. Neath, Student Member, IEEE, Akshya K. Swain, Member, IEEE, Udaya K. Madawala, Senior Member, IEEE, and Duleepa J. Thrimawithana, Member, IEEE

Abstract—Bidirectional inductive power transfer (IPT) systems are suitable for applications that require wireless and two-way power transfer. However, these systems are high-order resonant networks in nature and, hence, design and implementation of an optimum proportional–integral–derivative (PID) controller using various conventional methods is an onerous exercise. Further, the design of a PID controller, meeting various and demanding specifications, is a multiobjective problem and direct optimization of the PID gains often lead to a nonconvex problem. To overcome the difficulties associated with the traditional PID tuning methods, this paper, therefore, proposes a derivative-free optimization technique, based on genetic algorithm (GA), to determine the optimal parameters of PID controllers used in bidirectional IPT systems. The GA determines the optimal gains at a reasonable computational cost and often does not get trapped in a local optimum. The performance of the GA-tuned controller is investigated using several objective functions and under various operating conditions in comparison to other traditional tuning methods. It was observed that the performance of the GA-based PID controller is dependent on the nature of the objective function and therefore an objective function, which is a weighted combination of rise time, settling time, and peak overshoot, is used in determining the parameters of the PID controller using multiobjective GA. Simulated and experimental results of a 1-kW prototype bidirectional IPT system are presented to demonstrate the effectiveness of the GA-tuned controller as well as to show that gain selection through multiobjective GA using the weighted objective function yields the best performance of the PID controller.

Index Terms—Contactless power transfer, electric vehicles (EVs), inductive power transmission.

I. INTRODUCTION

Inductive power transfer (IPT) technology is now recognized as an efficient means of transferring power from one system to another “wirelessly or with no physical contacts.” This technology has the ability to operate in hostile environments being unaffected by dirt and moisture and has now evolved into a stage where it can transfer power at efficiencies as high as ~94%. Consequently, IPT systems are used in numerous applications, ranging from low-power biomedical implants up to high-power materials handling systems [1]–[3]. Recently, the focus has been on developing IPT-based systems for wireless charging of electric vehicles (EVs), which is more convenient and more tamper proof than conventional plug-in or hard-wired chargers. Furthermore, bidirectional IPT systems have also been proposed and developed for applications that require two-way power flow. Vehicle-to-grid (V2G) or G2V is a prime example [4]–[7].

Usually, power-handling capability of IPT systems is improved by providing series, parallel, or a combination of series and parallel compensation for coil reactances [8]–[10]. As a consequence, these systems invariably become high-order resonant networks, which are complex in nature and are difficult to both design and control, given that the frequency of operation is in the range of 10–50 kHz [11], [12]. Power flow in IPT systems can either be unidirectional or bidirectional, but irrespective of the direction of power flow, the system generally requires two separate controllers, which are dedicated to control the converters on each side of the system. Each controller regulates either the voltage or current, produced by its converter, to control the power flow. To keep switching losses to a minimum, the voltage and current are preferably controlled through phase modulation. In contrast to unidirectional systems, bidirectional IPT systems are even higher order resonant networks and more complex. The majority of these systems have been designed in the past using relatively simple steady-state models [13]–[16]. A dynamic state-space model for bidirectional IPT systems has recently been proposed and validated, and analysis has also been presented to show that decentralized or separate controllers can be used to control the power flow in bidirectional IPT systems [17]. Although proportional–integral (PI) and proportional–integral–derivative (PID) controllers have been proposed and implemented to regulate the power flow in bidirectional IPT systems, it has only been for the purpose of verifying a model or particular control strategy [10], [19], [20]. As such, no attempt has been made to optimize the controller design in relation to achieving the best possible dynamic performance of a bidirectional IPT system and this paper addresses this need by proposing a controller optimization technique.

Various tuning rules have been proposed in the past to determine parameters of PID controllers. The most popular among them is the Ziegler–Nichols (ZN) ultimate-cycle tuning method.
Although these methods perform well for lower order processes, they often result in suboptimal performance, particularly for higher order and nonlinear systems. For example, the ZN method may cause high overshoots, large oscillations, and longer settling times for higher order systems [21]. The bidirectional IPT system, being a higher order resonant network, falls into this category and the task of tuning PID gains for this system is, therefore, a major challenge. One of the most efficient methods of tuning PID parameters for such systems is through direct optimization, which often requires a solution to a nonconvex problem. Various other methods such as refined ZN and pole placement [20], [22] have also been proposed to obtain the optimum PID parameters. Majority of tuning methods used for higher order systems are based on model reduction techniques. However, these techniques along with direct optimization are not appropriate for bidirectional IPT systems, as IPT systems are composed of high-order resonant circuits and operated near the resonant frequency. Controllers designed using all these techniques have poor performance and are not appropriate for optimally controlling bidirectional IPT systems. An alternate approach to optimize the parameters is to use gradient-free optimization methods such as genetic algorithms (GAs), evolutionary computation, particle swarm optimization, etc. [23]. These methods are simple to apply and can readily incorporate practical meaningful performance characteristics into the PID controller design and are not affected by the high-order nature of the system and fitness function.

This paper, therefore, proposes a GA to tune the parameters of a PID controller taking various objectives (fitness) functions into consideration, to achieve a controller with optimal performance. Since the chosen performance criterion to control power is often a weighted combination of various performance characteristics such as rise time, settling time, percentage over-shoot and integral of error squared, the PID parameter optimization problem is formulated in a multiobjective optimization framework and solved using a GA. Simulated performance of the proposed GA-based PID controller is compared with some of the well-known tuning methods to investigate the optimal response and the best balance between performance and robustness. Finally, measured results of a 1-kW prototype bidirectional IPT system, implemented with a GA-based PID controller, which uses a multiobjective fitness function, are presented to demonstrate the validity, performance and robustness of the optimum controller design.

II. BIDIRECTIONAL IPT SYSTEM

Fig. 1 shows a typical bidirectional IPT system, consisting of a primary and a secondary side. The secondary circuit, which receives power from the primary through an air gap, is typically referred to as the pickup. The primary and the pickup use identical electronic circuitry, comprising a converter, an inductor–capacitor–inductor (LCL) resonant network with a series capacitor and a dedicated controller. The controllers are independent of each other and operate the converters on both sides to regulate the power flow across the air gap. The primary controller operates the primary-side converter, which is connected to the LCL resonate network to produce a constant sinusoidal current at a desired frequency $f_0$ in the primary winding, represented by the coil $L_{pt}$. This primary winding is commonly referred to as the primary track or the primary pad in IPT applications. The LCL circuits on both sides of the system are tuned to the frequency of track current $i_{pt}$ generated by the converter on the primary side. In a bidirectional IPT system, the magnitude and/or phase angle of the voltage vector produced by the pickup converter can be controlled with respect to the voltage vector produced by the primary converter to regulate the magnitude and direction of power flow, as described later.

Assume that the primary-side converter of the bidirectional IPT system, shown in Fig. 1, produces a reference sinusoidal voltage $v_{pr}$ at an angular frequency $\omega$, and the track current $i_{pt}$ is held constant by the primary-side controller. Since the inductor $L_{pt}$ is magnetically coupled to the secondary or the pickup coil $L_{st}$, a voltage is induced across $L_{st}$ due to $i_{pt}$. The induced voltage $v_{sr}$ in the pickup coil can be given by

$$v_{sr} = j\omega M i_{pt}$$

where $M$ represents the mutual inductance between the windings $L_{pt}$ and $L_{st}$ and can be given by

$$M = k \sqrt{L_{pt} L_{st}}$$

where $k$ is the coupling coefficient of the system, which typically is in the range of 0.1–0.3. As such, the coupling between the primary and secondary of an IPT system is significantly less than that of a traditional transformer or an induction motor, which have coupling coefficients greater than 0.95.

The pickup may be operated as a source or a sink by the controller and, despite the mode of operation, the voltage $v_{pr}$ reflected onto the track can be expressed by [6]

$$v_{pr} = j\omega M i_{st}.$$  

If the LCL circuits on both primary and pickup sides are tuned to the angular frequency $\omega$ of the current then [6]  

$$\omega^2 = \frac{1}{L'_{pi} C_{pi}} = \frac{1}{L_{pt} C_{pt}} = \frac{1}{L'_{si} C_{si}} = \frac{1}{L_{st} C_{st}}.$$  

This implies that $L'_{pi} = L_{pt}$ and $L'_{si} = L_{st}$, where $L'_{pi}$ and $L'_{si}$ are defined as

$$L'_{pi} = L_{pi} - \frac{1}{\omega C_{pi}},$$

$$L'_{si} = L_{si} - \frac{1}{\omega C_{si}}.$$
Under these conditions, it can be shown that the currents \(i_{pi}\) and \(i_{pt}\) of the primary are given by
\[
i_{pi} = j \frac{v_{pi}}{\omega L_{pt}} \quad (7)
\]
\[
i_{pt} = -j \frac{v_{pt}}{\omega L_{pt}} \quad (8)
\]
Similarly, the input and output currents of the pickup circuit can be given by
\[
i_{si} = -j \frac{v_{si}}{\omega L_{si}} \quad (9)
\]
\[
i_{st} = j \frac{v_{st}}{\omega L_{st}} \quad (10)
\]
Solving for \(i_{st}\) using (1)–(10),
\[
i_{st} = \frac{M}{L_{st} \omega L_{pt}} v_{pi}. \quad (11)
\]
If the equivalent ac voltage of the input voltage to the pickup-side converter is given by \(v_{si} \angle -\theta\), then the power input \(P_{si}\) of the pickup is given by
\[
P_{si} = Re : \{v_{si}(i_{st})^*\}. \quad (12)
\]
Substituting (8) into (9),
\[
P_{si} = \frac{M}{L_{st} \omega L_{pt}} |v_{pi}| \sin(\theta). \quad (13)
\]
It is evident from (13) that maximum power transfer takes place when the phase difference \(\theta\) between the primary and pickup voltage vectors is \(\pm 90^\circ\). A leading phase angle constitutes power transfer from the pickup to the primary, while a lagging phase angle enables power transfer from the primary to the pickup. As evident from (13), for any given \(v_{pi}\) and \(v_{si}\), the amount and direction of power flow between the primary and the pickup can be regulated by controlling both the magnitude and relative phase angle of the voltage vectors generated by the converters [6].

### III. DYNAMIC MODEL

A bidirectional IPT system can be schematically represented by the circuit model shown in Fig. 2. A state-space model to predict the dynamic behavior of a bidirectional IPT system can be derived from this circuit model. In developing the state-space model, the currents through the inductors and the voltages across the capacitors are taken as the state variables. Thus, the eight-order state-variable vector \(x\) can be defined as
\[
x = \left[ x_1 \ x_2 \ x_3 \ x_4 \ x_5 \ x_6 \ x_7 \ x_8 \right]^T
\]
\[
= \left[ i_{pi} \ v_{cpi} \ v_{pt} \ i_{pt} \ i_{si} \ v_{csi} \ v_{st} \ i_{st} \right]^T. \quad (14)
\]

The inputs to the state-space system are the voltages produced by the primary converter \(v_{pi}\) and the pickup converter \(v_{si}\). Thus, the input vector \(u\) can be given by
\[
u = \left[ u_1 \ u_2 \right]^T = \left[ v_{pi} \ v_{si} \right]^T. \quad (15)
\]
Similarly, the outputs of the state-space system model are the primary winding current \(i_{pt}\) and the pickup input current \(i_{si}\). Thus, the output vector can be given by
\[
y = \left[ y_1 \ y_2 \right]^T = \left[ i_{pt} \ i_{si} \right]^T. \quad (16)
\]

The state-space model of the system can be expressed as
\[
\dot{x} = Ax + Bu \quad (17)
\]
\[
y = Cx + Du \quad (18)
\]
where \(A\) is the system matrix, \(B\) is the input matrix, \(C\) is the output matrix, \(D\) is the feed-through matrix, and \(x\) is the state variable matrix. For given circuit parameters, these matrices can be evaluated as discussed in [17].

#### A. Relative Gain Array Analysis

The relative gain array (RGA), introduced in [24], is a heuristic method to predict the degree of coupling or interaction in a multivariable system. If \(u_j\) and \(y_j\) denote a particular input–output pair of a multivariable system, then the relative gain \(\lambda_{ij}\) between input \(j\) and output \(i\) is defined as
\[
\lambda_{ij} = \frac{\left(\delta y_i/\delta u_j\right)_{u_k \neq j}}{\left(\delta y_i/\delta u_j\right)_{y_k \neq j}} \quad (19)
\]
where \((\delta y_i/\delta u_j)_{u_k \neq j}\) is the gain between input \(j\) and output \(i\) with all other loops open and \((\delta y_i/\delta u_j)_{y_k \neq j}\) is the gain between input \(j\) and output \(i\) with all other loops closed. The different elements of the RGA matrix provide important information about the interactions between inputs and output in a multiinput and multioutput system. The larger the RGA value the greater the interaction between the input and output [24], [25]. The RGA matrix of the bidirectional IPT system with the parameters summarized in Table I is calculated at the operating frequency of

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{pt}) = (L_{st})</td>
<td>25 (\mu)H</td>
</tr>
<tr>
<td>(L_{pt}) = (L_{st})</td>
<td>46.1 (\mu)H</td>
</tr>
<tr>
<td>(C_{pt}) = (C_{st})</td>
<td>2.47 (\mu)F</td>
</tr>
<tr>
<td>(C_{pt}) = (C_{st})</td>
<td>2.53 (\mu)F</td>
</tr>
<tr>
<td>(M)</td>
<td>5 (\mu)H</td>
</tr>
<tr>
<td>(\text{airgap})</td>
<td>48 mm</td>
</tr>
<tr>
<td>(V_{pin}) = (V_{sin})</td>
<td>160 V</td>
</tr>
<tr>
<td>(\theta)</td>
<td>(\pm 90^\circ)</td>
</tr>
<tr>
<td>(\alpha_p)</td>
<td>120°</td>
</tr>
<tr>
<td>(\eta)</td>
<td>(\sim 0.85)</td>
</tr>
<tr>
<td>(f_0)</td>
<td>20 kHz</td>
</tr>
<tr>
<td>(t_{samp})</td>
<td>25 (\mu)s</td>
</tr>
</tbody>
</table>

### Fig. 2. Equivalent circuit representation of a bidirectional IPT system.
the system, 20 kHZ, and is given in (20). As IPT systems typically operate in a small frequency band around the operating frequency, the RGA matrix at other frequencies is not important in analyzing the interactions between inputs and outputs

\[
|\Lambda| = \begin{bmatrix}
\lambda_{11} & \lambda_{21} \\
\lambda_{12} & \lambda_{22}
\end{bmatrix} = \begin{bmatrix}
1.71 & 0.89 \\
0.89 & 1.71
\end{bmatrix}.
\] (20)

According to (20), the RGA elements \(\lambda_{11}\) and \(\lambda_{22}\) at 20 kHZ are greater than 1. This indicates that there exists a strong interaction between \(v_{pi}\) and \(i_{pi}\) and between \(v_{si}\) and \(i_{si}\). Therefore, the pickup-side converter current \(i_{si}\) can be easily controlled by \(v_{si}\). Similarly, \(i_{pi}\) should be controlled or paired with the input \(v_{pi}\). Since the other RGA elements \(\lambda_{12}\) and \(\lambda_{21}\) are negative, this implies that the inputs \(v_{pi}\) and \(v_{si}\) should not be paired or controlled with \(i_{si}\) and \(i_{pi}\), respectively, as closing the loop will change the sign of the effective gain. From the RGA analysis, it can be observed that a controller can be designed using a decentralized approach to achieve the desired performance. Further details about interpreting the RGA elements can be found in [24]. Furthermore, in V2G systems, decentralized controllers are preferred as the primary and the pickup can be controlled independently, thus eliminating the need for communication between the two sides.

IV. BIDIRECTIONAL IPT PICKUP-SIDE CONTROLLER

Based on the RGA analysis presented in the preceding section, it has been concluded that a decentralized controller can be used to control the power flow in a bidirectional IPT system. Therefore, this paper only presents the design and optimization of the pickup-side controller and the primary side of the system is operated at a fixed phase angle using an open-loop controller. The pickup controller regulates the output power by measuring the power flowing into the load and controlling the magnitude of the voltage \(v_{si}\) applied to the pickup’s resonant network accordingly with (13). A simplified diagram depicting how the magnitude of the voltage \(v_{si}\) is controlled is shown in Fig. 3. The voltage \(v_{pi}\) applied to the input of the primary resonant network is shown in the top plot. The second and third waveforms show the switching signals applied to the switches in the left-hand leg of the full bridge, whereas the fourth and fifth waveforms show the control signals applied to the right-hand leg. As evident from Fig. 3, switches in each leg are driven with complementary waveforms with a phase delay/advance of \(\alpha_s/2\) with respect to \(v_{pi}\). The final plot shows the resultant voltage applied to the input of the pickup-side resonant network. As can be seen from Fig. 3, by increasing the phase angle \(\alpha_s\), the magnitude of the voltage \(v_{si}\) can be increased, thus increasing the power flow while keeping the phase shift \(\theta\) between the primary and pickup constant at 90°.

The root-mean-square (RMS) value of the fundamental voltage component produced by the pickup converter can be expressed as a function of the control variable \(\alpha_s\) through

\[
v_{si} = V_{sin} \frac{4}{\sqrt{2\pi}} \sin (\alpha_s)
\] (21)

where \(v_{sin}\) is the dc voltage of the active load supplied by the pickup-side converter.

Combining (21) with (12), the input power of the pickup can be given by

\[
P_{si} = \frac{8MV_{pin}V_{sin}}{\omega^2L_{pl}L_{st}} \sin (\alpha_p) \sin (\alpha_s) \sin (\theta)
\] (22)

where \(\alpha_p\) is the phase delay applied to the primary-side converter to control \(i_{pi}\) and \(v_{pin}\) is the dc voltage applied to the primary-side converter. Both \(\alpha_p\) and \(\alpha_s\) are time discrete variables with a sampling period \(t_{samp}\) equal to twice the converters switching frequency \(\omega\).

A. Controller Design

A discrete PID controller, with a sampling time of \(t_{samp}\), is used in the pickup to regulate the power flow in the bidirectional IPT system by controlling \(\alpha_s\). The transfer function of the discrete PID controller can be given by

\[
G_c (z) = K_p \left[ 1 + \frac{1}{T_i (1 - z^{-1})} + T_d (1 - z^{-1}) \right].
\] (23)

This is essentially the discrete equivalent of the continuous time PID controller given by

\[
G_c (s) = K_{pc} \left[ 1 + \frac{1}{T_{ic} s} + T_{dc} s \right].
\] (24)

The discrete PID gains in (23) are related to the continuous PID gains of (24) by the following relations [27]:

\[
K_p = K_{pc} \left[ 1 - \frac{t_{samp}}{2T_{ic}} \right], \quad T_i = \frac{K_{pc} T_{ic}}{K_p t_{samp}}, \quad T_d = \frac{K_{pc} T_{dc}}{t_{samp} K_p}
\] (25)

To achieve a fast and stable response, it is essential to determine the optimum values of the proportional gain \(K_p\), integral time \(T_i\), and derivative time \(T_d\) of the PID controller. Over the past several decades, different methods have been proposed to
determine PID gain parameters, which have been summarized in [28] and the references therein. The most popular among them is the ZN method [20], which computes the PID gains from

\[ K_{pc} = 0.6K_u, \quad T_{ie} = \frac{T_u}{2}, \quad T_{dc} = \frac{T_u}{8} \]  

where \( K_u \) and \( T_u \) denote, respectively, the ultimate gain and ultimate period of the system. Another PID tuning method is proposed by Chien et al. [29], which determines the controller gains from

\[ K_{pc} = 0.6\frac{T_p}{\tau}, \quad T_{ie} = T_p, \quad T_{dc} = 0.5T_p \]  

where \( T_p \) is the time constant and \( \tau \) is dead time of the process, which is obtained from open-loop step response. Furthermore, the pidtool function in MATLAB can be used to determine the PID parameters that have a target phase margin of 60°. These methods, however, often give a rough estimate of the controller gains and need to be further adjusted heuristically by the designer to get the desired closed-loop response. This approach works satisfactorily for lower order systems. However, when the order of the system becomes high, as in case of bidirectional IPT systems, determination of PID gains subject to various control objectives becomes increasingly difficult. Therefore, in this study, the problem of PID controller tuning has been formulated as a multiobjective optimization problem and the optimum gains are determined using a GA.

1) PID Tuning Using GA: GAs have been used extensively in control system design during last few decades. The concept of GA in control design is briefly reviewed here for the sake of completeness.

GAs are stochastic search methods where an initial set of possible solutions (called as population) is modified in successive steps using the Darwinian principle of natural selection, recombination (crossover), mutation to yield an optimal solution. Each individual in the population is called a chromosome and represents a possible solution. GAs use three fundamental operators: selection, crossover, and mutation. Selection operator is used to select the best individuals (solutions) in a population. The crossover operator creates new individuals by mixing couples of selected individuals in a population and the mutation operator creates a new individual by randomly mutating a randomly selected part of a selected chromosome. Better convergence of the GA is achieved by both exploiting the search space by selection and crossover operators and exploring the search space for new information by mutation operator. The steps of implementing GA are as follows:

1) Generate an initial, random population of individuals (chromosomes) of fixed size where each individual (chromosome) represents a possible solution. The parameters \( K_p, T_i, \) and \( T_d \) of the PID controller are encoded following the method of concatenated, multiparameter-mapped fixed-point coding proposed in [30]. The structure of the chromosome is shown in Fig. 4. This chromosome is a sequence of three parts, with each part being 16 bits long. Since the starting generation of GA is random, the parameters of PID at the initial stage could make the system unstable. Therefore, the range of the controller parameters is selected such that the system remains stable within this range. The range of various gains is determined from a stability study of the system using the dynamic model.

2) Evaluate the fitness of each chromosome in the population.

3) Select the fittest members of the population.

4) Reproduce using a probabilistic method.

5) Implement crossover operation on the reproduced chromosomes.

6) Apply mutation operator.

7) Repeat from step 2) until a predefined convergence criterion is met.

a) Objective function: The most crucial step in applying GA is to choose the objective function, which is used to evaluate the fitness of each chromosome (i.e., PID parameters in this case). Researchers have used various objective functions; majority of them are [31] the following:

Integration of error

\[ J_1 = \int_0^\infty |e(t)| \, dt. \]  

Integration of error squared

\[ J_2 = \int_0^\infty e^2(t) \, dt. \]  

Integration of time waited error squared

\[ J_3 = \int_0^\infty te(t) \, dt. \]  

Although these objective functions provide satisfactory results in some applications, they cannot directly incorporate some of the controller design parameters such as peak overshoot, rise time and settling time. Since our objective is to determine the optimal values of PID parameters, which give the smallest overshoot, fastest rise time and quickest settling time, in this study the following objective function is selected:

\[ J_4 = (1 + os)(c_r t_r + c_s t_s) \]  

where \( os, t_r, \) and \( t_s \) represent, respectively, the overshoot, rise time, and settling time; \( c_r \) and \( c_s \) are two constants to be decided by the user. Moreover, the performance of the PID controller using different objective functions is investigated for comparison.

Fig. 5 shows the fitness of the best controller over a range of generations, using the \( J_4 \) fitness function. As can be seen, initially the fitness of the controller is high around 0.015, but as the number of generations increases, the fitness of the best controller improves. This continues until after about 50 generations where the optimum solution is found. With the optimal solution, the controller has a fitness of around 0.011. GA-based methods often require more computation time compared with other traditional methods to give an optimal solution. The convergence of the GA algorithm depends on various factors. However, once
Fig. 5. Fitness function of the GA using the $J_4$ fitness function.

**TABLE II**

<table>
<thead>
<tr>
<th>Objective function</th>
<th>$K_p$ $10^{-3}$</th>
<th>$T_i$ $10^{-6}$</th>
<th>$T_d$ $10^{-6}$</th>
<th>$os$</th>
<th>$t_r$ $10^{-3}$</th>
<th>$t_s$ $10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J_1$</td>
<td>11.524</td>
<td>38.47</td>
<td>70.44</td>
<td>0.60</td>
<td>1.7</td>
<td>2.4</td>
</tr>
<tr>
<td>$J_2$</td>
<td>96.862</td>
<td>179.37</td>
<td>7.65</td>
<td>1.12</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>$J_3$</td>
<td>96.862</td>
<td>183.37</td>
<td>8.53</td>
<td>1.15</td>
<td>1.2</td>
<td>2.4</td>
</tr>
<tr>
<td>$J_4$</td>
<td>88.350</td>
<td>94.75</td>
<td>6.21</td>
<td>1.13</td>
<td>0.5</td>
<td>0.9</td>
</tr>
</tbody>
</table>

we get an optimal solution from GA, they are more robust compared to other methods. The GA shown in Fig. 5 took 3 h to complete; but as can be seen, the optimal solution was found within about half an hour.

The GA was run with the four objective functions $J_1 - J_4$ and the results of the GA are shown in Table II. As can be seen, the objective function $J_4$ gives the controller with best rise time and settling time with an acceptable percentage overshoot.

V. RESULTS

In order to determine the performance of the controller gains determined in the preceding section, the response of a bidirectional IPT system to a step change in reference power were compared.

The circuit parameters of the IPT system, used to verify the performance of the proposed controllers through simulations on PLECS and experimental results gathered from a prototype converter, are given in Table I. A photo of this prototype bidirectional IPT system, which can transfer about 1 kW over an air-gap of 48 mm at an efficiency of 85%, is shown in Fig. 6. In each of the scenarios considered in this section, the phase shift $\theta$ between $v_{pi}$ and $v_{si}$ was maintained at 90° and the phase angle $\alpha_s$ was adjusted by the pickup-side controller to regulate the power flowing between the primary and pickup.

A. Simulated

The response of the IPT system when following a step change in reference output power was investigated using PLECS, a MATLAB Simulink-based software package. At 0 ms, a step change in the reference power level was introduced, where the power level was changed from 0 to $-1$ kW, which corresponds to power flowing in the forward direction from the primary to pickup. Under such conditions, the step response of the power flowing into the pickup-side converter is shown in Fig. 7. The first response was derived when controlled using the controller with gains determined from the ZN method. The controller gains derived from the CHR method resulted in a response shown in the second plot whereas the gains obtained from the ANA method yielded the response shown in the third plot. The final plot shows the response from the GA-tuned controller. As evident from Fig. 7, there are significant oscillations in the power flow with the ZN controller. However, the CHR, the ANA, and the GA controllers results in a response with no oscillations and a relatively fast response.

The response of a bidirectional IPT system to a step change in the power reference is somewhat different when the power flow is reversed. As such, it is essential to verify that the controller gains derived in the preceding section results in a stable and fast response when the power is flowing in the reverse direction (from the pickup to the primary). Fig. 8 shows the step response of the system when following a power reference that
Fig. 8. Simulated power transfer $P_{\text{si}}$ (in kilowatts) in the reverse direction for four different controllers.

Table III

<table>
<thead>
<tr>
<th>Controller</th>
<th>$K_p$</th>
<th>$\tau_i$ (\micro s)</th>
<th>$\tau_d$ (\micro s)</th>
<th>$%$ Over Shoot</th>
<th>Rise Time (ms)</th>
<th>Setting Time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZN</td>
<td>0.0596</td>
<td>16.31</td>
<td>4.077</td>
<td>28.2</td>
<td>0.16</td>
<td>&gt; 5</td>
</tr>
<tr>
<td>CHR</td>
<td>0.0840</td>
<td>99.06</td>
<td>51.28</td>
<td>1.7</td>
<td>0.51</td>
<td>0.748</td>
</tr>
<tr>
<td>ANA</td>
<td>0.0182</td>
<td>27.23</td>
<td>1.35</td>
<td>1.04</td>
<td>0.62</td>
<td>0.90</td>
</tr>
<tr>
<td>GA</td>
<td>0.0883</td>
<td>94.75</td>
<td>6.22</td>
<td>1.22</td>
<td>0.40</td>
<td>0.61</td>
</tr>
</tbody>
</table>

changes from 0 to $+1$ kW at 0 ms. Similarly, to the response shown by the system when power was flowing in the forward direction, oscillations can be observed in the power when the pickup is controlled derived using the ZN tuning method. However, the magnitudes of oscillations in the step responses are much smaller in comparison to the response yielded when the IPT system was transmitting power in forward direction.

Table III summarizes the gain parameters of the four controllers together with the percentage overshoot and settling time when power flow is in the reverse direction. As can be seen, with the ZN-tuned controller, there is a large overshoot. The GA controller has the fastest response with no overshoot; therefore, this controller offers the best performance, and is the most suitable for controlling the power flow in a bidirectional IPT system.

B. Experimental

After verifying the performance of the controllers through simulations, the controllers were implemented on a 1-kW prototype bidirectional IPT system, shown in Fig. 6, using a Texas Instruments TMS28335 microcontroller.

The results obtained from this prototype system when controlled using the controller with gain values derived using the GA are shown in Figs. 9 and 10. The waveforms when delivering power to the pickup load is depicted in Fig. 9, whereas Fig. 10 shows the results gathered from the system when power flow is in the reverse direction. Fig. 9 shows a step change in reference power from 0 to $+1$ kW. As evident from these waveforms, there are no significant oscillations or overshoots in either power or currents. Conversely, Fig. 10 shows the system operating with a step change in reference power from 0 to $+1$ kW, which also shows an oscillation-free response. The settling time of the experimental system is 0.92 ms compared to 0.86 ms for the simulated system. The results obtained from the experimental setup in both directions are similar to the simulated results, thus, confirming the validity of the simulations.

Fig. 11 depicts the power flowing from the pickup converter to the primary side of the system, over a range of operating conditions. As evident from these waveforms, the controller is capable of regulating the bidirectional power flow over a range of power levels. Similarly, to the previous results, the controller responds faster in controlling the forward power flow indicated by negative values, in comparison controlling the reverse power flow. To verify the robustness of the proposed GA PID controller, experimental results were obtained while varying the system...
parameters. Fig. 12 shows the response of the system to a 15% decrease in magnetic coupling, $M$. From Fig. 12, it is evident that the controller is still capable of controlling the power flow and that the variation in coupling has not affected the stability of the system. However, the decrease in magnetic coupling has increased the closed-loop response time. Furthermore, Fig. 13 shows experimental results with a 15% increase in the primary tuning capacitance $C_{pt}$. The controller is still maintaining the output at 1 kW but exhibits a faster response time. However, increasing the capacitance will cause the system to operate at a nontuned frequency increasing the losses and reducing the efficiency, which is evident from the relatively larger current $i_{si}$.

VI. Conclusion

Bidirectional IPT systems are essentially higher order systems and therefore conventional approaches of designing PID controllers, especially those based on ZN and various model reduction techniques do not yield satisfactory performance. Therefore, a systematic approach based on GA has been proposed to tune the PID parameters. Since the objective function plays a crucial role in GA, the performances of several GA optimized PID controllers, which used different objective functions, have also been investigated in detail. It was shown that in order to achieve desired power regulation performance, the controller has to meet many conflicting objectives. By judiciously selecting the objective function, which was a weighted combination of settling time, rise time, and peak overshoot (weighted objective), the parameters of PID controller have been determined using a multiobjective GA. Simulated performance of the GA-based PID controller with various objective functions has been presented in comparison to other well-known methods of PID design such as the methods of ZN, Chien et al., and PID optimization tools for MATLAB. The results of simulation convincingly illustrate that GA-based PID controller, which used weighted objective functions, offers the best balance between performance and robustness. The effectiveness of a GA-based PID controller has further been experimentally validated by the measured performance of a 1-kW prototype bidirectional IPT system. Although the proposed GA-designed PID controller has a significantly higher computational time when compared to traditional methods, controllers designed with GA are more robust and stable, as they take account of the discrete controller and sampling time in their design.

REFERENCES


Michael J. Neath (S’08) received the B.E. (Hons.) degree in electrical engineering from The University of Auckland, Auckland, New Zealand, in 2011, where he is currently working toward the Ph.D. degree in power electronics.

His current research interests include the fields of power electronics, inductive power transfer, wireless electric vehicle charging, and vehicle to grid systems.

Udaya K. Madawala (M’95–SM’06) received the B.Sc. (Hons.) degree in electrical engineering from the University of Moratuwa, Moratuwa, Sri Lanka, in 1987, and the Ph.D. degree in power electronics from The University of Auckland, Auckland, New Zealand, in 1993.

In 1997, he joined as a Research Fellow the Department of Electrical and Computer Engineering, The University of Auckland, where he is currently an Associate Professor. His current research interests include the fields of power electronics, inductive power transfer, and renewable energy.

Dr. Madawala is an active IEEE volunteer and is an Associate Editor for the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and the IEEE TRANSACTIONS ON POWER ELECTRONICS. He is a Member of the Power Electronics Technical Committee of Industrial Electronics Society and the Sustainable Energy Systems Committee of IEEE Power Electronics Society.

Duleepa J. Thrimawithana (M’09) received the B.E. degree (with first-class Hons.) in electrical engineering and the Ph.D. degree in power electronics from The University of Auckland, Auckland, New Zealand, in 2005 and 2009, respectively.

From 2005 to 2008, he worked, in collaboration with Tru-Test Ltd., Manukau, New Zealand, as a Research Engineer in the areas of power converters and high-voltage pulse generator design. In 2008, as a Part-Time Lecturer he joined the Department of Electrical and Computer Engineering, The University of Auckland.

Dr. Thrimawithana is an active IEEE Member and is the Chairman of the Joint Chapter of IEEE Industrial Electronics Society and the IEEE Industrial Applications Society in New Zealand (North).