Extended Summary

High Efficiency Isolated DC/DC Converter using Series Connection on Secondary Side

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Keywords: DC/DC converter, isolated converter, series voltage compensation, current resonance

This paper proposes a new topology for an isolated DC/DC converter using series voltage compensation. The input voltage fluctuation is compensated by the auxiliary circuit that outputs only the fluctuation of the output voltage. One of the advantages of the proposed circuit is that a high efficiency can be achieved when the input voltage is almost equal to the nominal input voltage because the power of the auxiliary circuit becomes considerably lower than the input power. Generally, large fluctuations of the DC bus voltage are not generated for long periods, and as a result, the converter loss can be reduced. The suitability of the proposed circuit was confirmed by performing an experiment and loss analysis.

Fig. 1 shows the configuration of the proposed converter using series connection on the secondary side. The proposed system consists of two power converters, which are connected in series at the output side by using a transformer. The main circuit consists of a resonant type half-bridge converter with an isolation transformer. Zero current switching (ZCS) is achieved by the resonance circuit between the leakage inductance of the transformer and the resonance capacitor in the DC part, in order to achieve a high efficiency. On the other hand, the auxiliary circuit is a full-bridge converter used for regulating the output voltage. The output voltage of the auxiliary circuit is added to the output of the main circuit by the transformer. In other words, the auxiliary circuit compensates only the fluctuation voltage against the output voltage commands. Therefore, the converter loss is decreased.

Fig. 2 presents the efficiency of the proposed converter at a constant load (Output voltage: 12 V) when the input voltage fluctuates by ±25%. In order to confirm the suitability proposed converter, it was tested. The maximum efficiency achieved was 96.2% is obtained, as shown in Fig. 2, when the input voltage is almost equal to the nominal input voltage. The efficiency in the boost mode is lower than that in the buck mode because in the boost mode the current is increased by the circulation current between the auxiliary circuit and the rectifier. Consequently, the conduction loss increases because of the high circulating current.

Fig. 3 shows the input current of the transformer and the terminal voltage of $S_m$. In these modes, reference mode, boost and buck mode accordingly, the half-bridge converter maintain at ZCS. A switching frequency of approximately 200kHz was confirmed.

Fig. 1. Proposed circuit

Fig. 2. Characteristics of efficiency for the input voltage fluctuations

Fig. 3. Input current of the transformers and the terminal voltage of $S_m$ (Load:100 W)
Multi-rating Electronic Ballast for Fluorescent Lamps based on Operating Frequency Determination

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**Keywords:** ballast, fluorescent lamps, automatic detection, frequency determination

The fluorescent lamps must be used with electronic ballasts specifically designed for each lamp power rating. A mismatch between ballast and lamp ratings usually results in damage to both the lamp and the ballast circuit. With a large number of different ratings of fluorescent lamps, an equally large stock of specifically rated electronic ballasts is required. The multi-rating fluorescent ballast is a solution to eliminate this problem. The controller of the multi-rating ballast must regulate and deliver the correct power to a lamp of unknown rating. Thus, the lamp rating detection algorithm must be accurate and sufficiently fast. The voltage detection method can differentiate between lamp power ratings by using the operating lamp voltage. However, the lamp voltage after striking (ignition) varies with the lamp temperature, age, and manufacturer. Thus, different lamp ratings may have overlapping voltage ranges, which can result in misidentification of the lamp. In addition, noise can interfere with the voltage, and adding a filter may increase the cost of the system.

This paper presents a multi-rating electronic ballast for fluorescent lamps based on operating frequency determination. The lamp rating detection algorithm is composed of multi-step lamp power regulation and the trapezoidal possibility weight determination based on the lamp operating frequency. After ignition, the multi-step lamp power regulation is started with the lowest power command. For example, the 16 W power command is used for the T8 series lamps. In the power control loop, the operating frequency is determined and collected in the controller. This frequency is used to classify the 18 W (lowest) from the group. If the measured frequency is within the valid range, then no further decision is necessary and the controller proceeds to the running state. However, due to the variation between lamp manufacturers, bulb age, and temperature, the running frequency is not necessarily constant. We experimentally verified that the operating frequency varies during our lamp power regulation experiment.

With the proposed method, the frequency is generating by the micro-controller itself which is not interfered by noise. And the multi-step power regulation constrains the lamp operating condition during the detection as well. The Detection results of the proposed method and the voltage detecting method are shown in Table 1. This algorithm results in a 100% detection rate of all tested lamps. For the testing with very old lamps, the inaccurate detection is occurred but the protection algorithm stops the ballast operation due to the rectifying effect.

**Table 1. Voltage detecting method (V.D.) VS Proposed frequency detecting method results**

<table>
<thead>
<tr>
<th>Lamp rating</th>
<th>V.D. Method</th>
<th>Proposed method</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Detection rates</td>
<td>100, 60, 100, 70, 100</td>
<td>100, 100, 100, 100, 100</td>
</tr>
<tr>
<td>% Type I error</td>
<td>0, 0, 0, 0, 0</td>
<td>0, 0, 0, 0, 0</td>
</tr>
<tr>
<td>% Type II error</td>
<td>0, 0, 0, 0, 0</td>
<td>0, 0, 0, 0, 0</td>
</tr>
</tbody>
</table>

- type I error: the false positive - the error of rejecting lamp when it is actually at rating
- type II error: the false negative - the error of failing to reject a lamp when it is in fact not at rating
Method for On-line Estimation of Electrical Motor Parameter Variation and Current Sensor Offset for SPM Motor

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Keywords: current simulator, parameter identification, current sensor offset, surface permanent magnet synchronous motor

The servo system of a permanent magnet (PM) motor should always maintain fine torque and fine speed responses. Accurate motor parameter identification is necessary for the PM motor servo system because the current control system is designed by considering the electric parameters of the PM motor. However, the motor parameters vary with the age of the motor and temperature. Moreover, current sensors have offset values. When the current sensor has offset values, the PM motor servo system produces torque ripple. In order to overcome these problems, this paper proposes a new real-time estimation method for both current sensor offsets and electrical parameters (resistance $R_a$, inductance $L_a$, and magnetic flux $\phi_{fa}$) of the surface permanent magnet (SPM) motor. The proposed method involves the use of a real-time algorithm and a current simulator, which is operated using a DSP software system. In order to accurately estimate the motor parameters, the proposed method is using estimate currents, DC terms of sensor currents, and nominal motor parameter value. The experimental results of this study confirm that the proposed method satisfactorily estimates the current sensor offset of the $U$ phase and $V$ phase, as well as the electrical motor parameters $R_a$, $L_a$, and $\phi_{fa}$ accurately.

Fig. 1 shows the experimentally obtained current waveforms including parameters variation and current sensor offsets. The parameter variations are responsible for the estimation error of the current simulator, and the sensor offsets cause current ripple. In the proposed method, the electrical parameters $R_a$, $L_a$, and $\phi_{fa}$ are determined by varying the nominal parameters $R_o$ and $L_o$.

Fig. 2 shows the experimental system, and Fig. 3 shows the current waveforms obtained experimentally by using the proposed method for the real-time identification and tuning of motor parameters and current sensor offsets. Table 1 shows the estimation results. Thus, the proposed method estimates the electrical motor parameters and the current sensor offsets, well.

Table 1. Comparison of the estimated parameters and estimated sensor offsets with actual parameters and sensor offsets

<table>
<thead>
<tr>
<th>Actual parameters</th>
<th>Estimated parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$ $\times 0.8$</td>
<td>$\times 0.832$</td>
</tr>
<tr>
<td>$\beta$ $\times 1.3$</td>
<td>$\times 1.298$</td>
</tr>
<tr>
<td>$\Delta \phi$ $+30%$</td>
<td>$+30.9%$</td>
</tr>
<tr>
<td>$\Delta i_u$ $40\text{[mA]}$</td>
<td>$38.8\text{[mA]}$</td>
</tr>
<tr>
<td>$\Delta i_v$ $20\text{[mA]}$</td>
<td>$21.2\text{[mA]}$</td>
</tr>
</tbody>
</table>

Fig. 1. Experimental results of current waveforms including parameters variation and current sensor offsets

Fig. 2. Configuration diagram for the identification of both current sensor offsets and electrical parameter variation for the SPM motor

Fig. 3. Experimental results of current waveforms using the proposed method for the real-time identification and tuning of motor parameters and current sensor offsets
Single-Switch Equalization Charger Using Multiple Stacked Buck-Boost Converters for Series-Connected Energy-Storage Modules

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Keywords: energy-storage module, buck-boost converter, voltage equalization charger, Electric Double-Layer Capacitor (EDLC)

Series connections of energy-storage modules such as electric double-layer capacitors (EDLCs) and lithium-ion batteries result in voltage imbalance because of nonuniform module properties such as capacitance, internal impedance, self discharge rate, and environmental temperature. Such voltage imbalances cause premature degradation and lead to a decrease in available energy. Voltage equalizers are usually employed to mitigate or even eliminate such voltage imbalance in order to prolong cycle lives and to maximize available energies of the modules. However, conventional voltage equalizers based on traditional dc-dc converters require numerous switches and/or transformers as the number of series connections increases, and therefore, their costs and complexity tend to increase, while their reliability decreases.

This paper proposes a novel single-switch equalization charger using multiple stacked buck-boost converters for series-connected energy-storage modules. The basic topology of traditional buck-boost converters such as SEPIC, Zeta, and Ćuk converters can be used in developing the proposed equalization charger. In this paper, the SEPIC-based equalization charger is selected as a representative and discussed.

The proposed equalization charger consists of single switch and multiple stacked circuits composed of a diode, inductor, and coupling-capacitor, as shown in Fig. 1. Thus, the circuit complexity is considerably lower than that of conventional equalizers using multiple dc-dc converters. In addition, the switch is not connected to the module in parallel, and the coupling-capacitors protect the modules from being shorted in the case of short-circuit failure of the switch. Thus, the reliability of this equalization charger is considered to be higher than that of conventional equalizers.

The fundamental operating principles are presented in detail. All the modules are charged equally when their voltages are balanced. On the other hand, in the case of voltage-imbalanced conditions, only the module with the lowest voltage is charged preferentially. Operations of the proposed charger under the voltage-equalized and voltage-imbalanced conditions were mathematically generalized. As the charging proceeds, the charge currents decrease gradually, and the charger starts to operate in a discontinuous conduction mode (DCM). The operation in the DCM was also analyzed.

An experimental charging test using a 25 W prototype of the proposed equalization charger was performed for four series-connected EDLC modules whose initial voltages were intentionally imbalanced. A constant input current–constant voltage (CIC–CV) charge scheme, which controls an input current and one of the module voltages, was employed for the experimental charge test. The experimental results showed that the proposed equalization charger could charge the series-connected modules preferentially in the order of increasing module voltage and that all the modules eventually could be charged up to a uniform voltage level, as shown in Fig. 2.
Parallel Computing of Magnetic Field Analysis for Rotating Machines
Driven by Voltage Source on the Earth Simulator

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Keywords: Earth Simulator, parallel computing, domain decomposition, voltage source, three-dimensional finite element method

1. Introduction

We have developed a parallel computing method for rotating machines based on the domain decomposition method (DDM). In case that the electric circuits are taken into account in the 3-D FEM using the DDM, a lot of data communications for the electric circuit might be caused between subdomains, because coils are separated into multiple subdomains. Thus, it is necessary to develop a new method in order to reduce the data communications. Therefore, we develop a parallel computing method for rotating machines excited from voltage sources, in which the matrix-vector product for the electric equation in the coil region in each subdomain is calculated in order to reduce the data communications. Therefore, we developed a parallel computing method for rotating machines excited from voltage sources, in which the matrix-vector product for the electric equation in the coil region in each subdomain is calculated efficiently. The validity and the usefulness of the method is verified through the computation of an IPM motor excited from voltage source on the Earth Simulator, which is the vector-type parallel supercomputer in Japan.

2. Parallel Computing Method For Coupled Analysis with Electric Circuit

In the subdomain, the matrix equation, which takes into account the voltage source, is given as follows:

\[
\begin{bmatrix}
\frac{\partial G^{(i)}}{\partial A^{(i)}} \\
\frac{\partial G^{(j)}}{\partial A^{(j)}} \\
\frac{\partial E}{\partial A^{(i)}} \\
\frac{\partial E}{\partial A^{(j)}}
\end{bmatrix}
\begin{bmatrix}
\delta A^{(i)} \\
\delta A^{(j)} \\
\delta E \\
\delta A^{(j)}
\end{bmatrix}
= \begin{bmatrix}
G^{(i)} \\
G^{(j)} \\
E \\
0
\end{bmatrix}
= \begin{bmatrix}
V_0 + \sum_{j=1}^{n} \{F^{(j)}\} \\
V_0 + \sum_{j=1}^{n} \{F^{(j)}\} \\
0 \\
0
\end{bmatrix}
\]

\[
\begin{bmatrix}
\frac{\partial G^{(i)}}{\partial A^{(i)}} \\
\frac{\partial G^{(j)}}{\partial A^{(j)}} \\
\frac{\partial E}{\partial A^{(i)}} \\
\frac{\partial E}{\partial A^{(j)}}
\end{bmatrix}
\begin{bmatrix}
\delta A^{(i)} \\
\delta A^{(j)} \\
\delta E \\
\delta A^{(j)}
\end{bmatrix}
= \begin{bmatrix}
G^{(i)} \\
G^{(j)} \\
E \\
0
\end{bmatrix}
= \begin{bmatrix}
V_0 + \sum_{j=1}^{n} \{F^{(j)}\} \\
V_0 + \sum_{j=1}^{n} \{F^{(j)}\} \\
0 \\
0
\end{bmatrix}
\]

where \( i \) and \( j \) are subdomain number, \( n \) is the number of subdomains, \( E \) is voltage formula and \( \{F^{(j)}\} \) is given as follows.

\[
\{F^{(j)}\} = \begin{cases}
\frac{\partial E}{\partial A^{(j)}} \delta A^{(j)} & \text{(if } j \text{-th subdomain contains coil)} \\
0 & \text{(otherwise)}
\end{cases}
\]

The values of \( \frac{\partial E}{\partial A^{(j)}} \) and \( \delta A^{(j)} \) in Eq. (2) are the same in all subdomains.

In order to efficiently calculate the matrix-vector product of the row corresponding to \( \frac{\partial E}{\partial A^{(j)}} \) in the conjugate gradient (CG) method, the column vectors \( \{F^{(j)}\} \) of all subdomains are summed with communication after the independent evaluations of \( \{F^{(j)}\} \) in each subdomain.

Fig. 1 shows the example of analyzed domain, which is divided into two subdomains \( \Omega^{(1)} \) and \( \Omega^{(2)} \), and the coil region is also divided into two regions \( \Omega^{(1)}_{\text{coil}} \) and \( \Omega^{(2)}_{\text{coil}} \). Two matrix-vector products \( \{F^{(1)}\} \) and \( \{F^{(2)}\} \), which are evaluated in the regions \( \Omega^{(1)}_{\text{coil}} \) and \( \Omega^{(2)}_{\text{coil}} \), respectively, are summed with communications at each iteration of CG method.

3. Numerical Results

Fig. 2 shows the analyzed model of an IPM motor. The eddy current in the permanent magnets is taken into account. The number of elements is 5,788,908. This analysis is performed using 8 nodes (64 CPUs) of the renewed Earth Simulator, which is called ES2.

Table 1 shows the performance of the proposed method. The performance obtained on a single PC is also listed in the same table. The calculation using the single PC requires about 41 hours per step. The calculation for 180 steps will require about 7,428 hours (310 days), and is not practical. On the other hand, the calculation with proposed method using 8 nodes of ES2 was completed in 19 minutes per step. The proposed method is useful to design and develop motors.

<table>
<thead>
<tr>
<th>Methods</th>
<th>Number of CPUs</th>
<th>Number of time steps</th>
<th>Number of unknown variables</th>
<th>Elapsed time (min./step)</th>
<th>Total elapsed time (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single PC</td>
<td>64</td>
<td>180</td>
<td>6,698,762</td>
<td>41.2</td>
<td>2,476.0</td>
</tr>
<tr>
<td>ES2</td>
<td>8</td>
<td>180</td>
<td>6,698,762</td>
<td>41.2</td>
<td>2,476.0</td>
</tr>
</tbody>
</table>

*estimated
Evolution of Automotive Chopper Circuits Towards Ultra High Efficiency and Power Density

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Keywords: Dc-Dc converter, soft switching, high efficiency, automotive application

Recent global environmental issues have accelerated introduction of more efficient and energy saving technologies in many areas of daily life. Major energy consumption is the transportation, especially automobiles. The need for “cleaner” automobiles has created hybrid electric vehicles (HEV) and even pure electric vehicles (EV) and fuel cell electric vehicles (FCEV) could be commercially available in the near future.

DC/DC converters are used in automotive traction in order to optimise the power flow between the battery and traction motors. The power rating of DC/DC converters for HEV lies in the range between 30 and 90 kW, and it may be beyond 100 kW for EV and FCEV. The main design target points are often high power density and high efficiency which drives the research effort to improve both of them in the same time.

In this paper, several examples of high power density and high efficiency DC/DC converters for vehicles with an electric drive train are introduced. They are based on so-called SAZZ topology (Snubber assisted zero-voltage-zero-current transition topology) which offers soft switching at turn-on as well as turn-off for all switches. The considered power range of model converters is 8 to 30 kW with the switching frequency up to 100 kHz with IGBTs and 200 kHz with MOSFETs respectively. The main goal of the presented designs is reaching as high power density and efficiency as possible. The presented converter prototypes exhibit power density as high as 40 kW/litre and efficiency over 99%.

Prototypes presented as case studies are based on bi-directional SAZZ1 topology shown in Fig. 1. This topology allows a fully bi-directional power transfer with soft switching in wide load range. The prototypes are presented in Fig. 2 and Fig. 3 respectively. The design presented in Fig. 2 uses high current IGBTs to reduce the conduction losses. The resulting efficiency is 98% region in a broad load and conversion range. However, the power density suffers due to: using large high current IGBT modules, requirement of very high efficiency starting from low power levels (low main inductor ripple current) and relatively low operating frequency of 25 kHz. The prototype presented in Fig. 3 uses an approach based on CoolMOS technology. In this case, the high power density and the efficiency were set as the design targets. Optimal spatial component design as well as advanced water cooled thermal management were applied as well. The result is the ultra high efficiency in 99% region and power density as high as 40 kW/litre.
A Method for Reducing the Dead-Time Voltage and Impedance Voltage in a Series Voltage Compensator

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Keywords: series voltage compensator, dead time voltage, impedance voltage

Harmonic current generation, harmonic voltage distortion, and voltage flicker interference in power electronics equipment are serious problems. Input current harmonics and harmonic voltage distortion in a power system cause serious problems and accidents in power electronics equipment. Many groups have investigated these problems and have developed an active power filter and a voltage compensator with shunt and series converters for realizing a stable voltage supply. The series converter compensates for the fundamental voltage and harmonic voltage, while the shunt converter compensates for the fundamental current and harmonic current.

Since the series converter is inserted into the power system in series, the series transformer acts as a current transformer. Therefore, a primary current corresponding to the voltage transformation ratio flows into the inverter through an LC filter and a series transformer. Owing to the dead time, the output voltage, which is a square waveform, is generated even when references are zero volt. We define the error voltage as a superimposed voltage that consists of a dead-time voltage and an impedance voltage.

In a series voltage compensator, a quick response is often required, and therefore an open-loop control is used. We can observe the error voltage in the series converter with an open loop controller. Feedback controllers are sometimes designed for the voltage compensator, and the error voltage is not observed clearly in these cases.

The superimposed voltage, which consists of the dead-time voltage, LC filter voltage, and transformer impedance voltage, is generated as an output voltage in the series converter. The dead-time voltage is a square waveform with the same phase as the current and is constant when current flows into the inverter. An impedance voltage that consists of the LC filter voltage and transformer impedance voltage is proportional to the load current.

In this paper, we propose a method for reducing the superimposed voltage, which consists of the dead-time voltage and impedance voltage. Using this method, we can compensate for the fundamental voltage and harmonic voltage for loads ranging from a light load to rated loads.

We confirm the effectiveness of the method by performing experiments and obtaining the steady-state and transient characteristics of the series converter which are shown in Fig. 1 and Fig. 2.

Fig. 1. Experimental waveforms of the line-to-line voltage $V_{out uv}$, its FFT result, and the u-phase current $I_{invu}$ with the proposed method in the case of 100% load

Fig. 2. Waveforms of the line-to-line voltage $V_{out uv}$ and u-phase current $I_{invu}$ with the proposed method in the case of load changing from 50% to 100%
A Hypothesis Verification Method Using Regression Tree for Semiconductor Yield Analysis

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Keywords: semiconductor, yield analysis, regression tree analysis, attribute, hypothesis verification, failure cause identification

Several researchers have reported the regression tree analysis for semiconductor yield. However, the scope of these analyses is restricted by the difficulty involved in applying the regression tree analysis to a small number of samples with many attributes. It is often observed that splitting attributes in the route node do not indicate the hypothesized causes of failure. We propose a method for verifying the hypothesized causes of failure, which reduces the number of verification hypotheses.

In the semiconductor line of analysis, many types of products are simultaneously manufactured using the same technology. The process conditions are expected to be the same, and the failure cause may be the same even if the products are different. That is, the hypothesized cause of failure can be verified using plural results of regression tree analysis performed with two or more analysis data.

Table 1 shows the result obtained when the proposed method is executed with the data pertaining to four products: eight hypothesized causes of failure are extracted according to the order of the indices for the splitting attribute. Using the information in this table, we can efficiently identify the failure cause without depending on the engineer’s knowledge to a large extent. The failure cause (Equipment MET3) can be identified by sequentially verifying the hypothesized causes from the top rank in Table 1. Experiments performed in a real environment show that the proposed method is well suited for practical applications.

Using this method, we can expand the scope of application of the regression tree analysis to semiconductor yield.

Table 1. Integrated ordered list of attributes and analysis data

<table>
<thead>
<tr>
<th>No.</th>
<th>Attr</th>
<th>Prod.</th>
<th>t</th>
<th>Equipment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AET2</td>
<td>2</td>
<td>7.16</td>
<td>MET2, MET3</td>
</tr>
<tr>
<td>2</td>
<td>AET1</td>
<td>1</td>
<td>6.46</td>
<td>MET3</td>
</tr>
<tr>
<td>3</td>
<td>A_16</td>
<td>1</td>
<td>4.54</td>
<td>M_{10,3}, M_{11,4}</td>
</tr>
<tr>
<td>4</td>
<td>A_12</td>
<td>2</td>
<td>4.32</td>
<td>M_{12,2}</td>
</tr>
<tr>
<td>5</td>
<td>A_8</td>
<td>1</td>
<td>4.1</td>
<td>M_{13,3}</td>
</tr>
<tr>
<td>22</td>
<td>AET2</td>
<td>3</td>
<td>2.8</td>
<td>MET3</td>
</tr>
<tr>
<td>23</td>
<td>A_6</td>
<td>4</td>
<td>2.79</td>
<td>M_{14,5}</td>
</tr>
<tr>
<td>24</td>
<td>A_4</td>
<td>3</td>
<td>2.76</td>
<td>M_{14,1}, M_{14,2}</td>
</tr>
<tr>
<td>25</td>
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<td>4</td>
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<td>M_{14,1}, M_{15,3}</td>
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<tr>
<td>26</td>
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<td>4</td>
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<td>M_{14,4}</td>
</tr>
<tr>
<td>27</td>
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<td>4</td>
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<td>MET1, MET3</td>
</tr>
<tr>
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<tr>
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<td>3</td>
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<td>M_{14,2}</td>
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<tr>
<td>31</td>
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<td>32</td>
<td>A_4</td>
<td>3</td>
<td>1.99</td>
<td>M_{14,2}</td>
</tr>
</tbody>
</table>

In the conventional method shown in Fig. 1, we verify the hypothesized causes of failure for the ordered list of attributes $O_{d_k}$, which stores them in the order of the index for the splitting attribute. In Step 4, the order of selection of $O_{d_{k}}$ to identify the failure cause is decided by the engineer’s knowledge. This selection causes differences in the verification number, which are used to identify the failure cause.

Our method involves selecting sets of analysis data with the same cause of failure, extracting the hypothesis by applying the regression tree analysis separately to each set of analysis data, merging and sorting attributes according to the $t$ value, and identifying the failure cause.

In the conventional method, the order of selection of attributes $O_{d_{k}}$ is decided by the engineer’s knowledge. This selection causes differences in the verification number, which are used to identify the failure cause. In our method, the order of selection of attributes $O_{d_{k}}$ is decided by the engineer’s knowledge. This selection causes differences in the verification number, which are used to identify the failure cause.
Dynamic Analysis of 3 DOF Actuator Employing 3 D Finite Element Method

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1. Introduction
Recently, multi-degree-of-freedom actuators which can be operated in arbitrary axes come to attract attention because of the solution for efficiency, weight, size, and so on. Particularly, spherical actuators are expected to the application to the joints and eyeballs for robots. Under the circumstances, authors proposed a new three-degree-of-freedom spherical actuator, and confirmed the static characteristics by 3-D FEM.

In this paper, we predict dynamic characteristics of this actuator employing 3-D dynamic analysis, in which the magnetic field equation is combined with equations of electric circuit and three axes motion. The effect of each axis operation on other axes is clarified. The effectiveness of the analysis is confirmed by carrying out the measurement of a prototype.

2. Basic Structure
Fig. 1 shows the basic structure of a three-degree-of-freedom electromagnetic spherical actuator used in this study. This actuator is mainly composed of a mover with four interior magnets (Br = 1.4 T) and two sets of stators with six magnetic poles (500 turns of winding) arranged along Z-axis. The mover three-dimensionally rotates around a spherical bearing to keep the gap constant (0.7 mm) during the motion. The outer diameter of the stator is 150 mm, and the outer diameter of the mover is 60 mm, respectively.

3. Analysis Method
The magnetic field equation is combined with electric circuit equation and motion equation as follows:

\[ J = \text{rot} \ T \] (1)
\[ \text{div} \left( \mu (T_m + T_e + T_0 - \text{grad} \Omega) \right) = 0 \] (2)
\[ \text{rot} \left( \frac{1}{\sigma} \text{rot} T_e \right) = -\frac{\partial}{\partial t} \left( \mu (T_m + T_e + T_0 - \text{grad} \Omega) \right) \] (3)

Where \( T_m, T_e, \) and \( T_0 \) are current vector potentials of equivalent magnetizing current density, eddy current density and forced current density respectively, \( \mu \) is the permeability, and \( \sigma \) is the electrical conductivity. The motion equation is given as follows.

\[ I_i \frac{d^2 \theta_i}{dt^2} + D_i \frac{d \theta_i}{dt} + T_s i = T_m i \ (i = x, y, z) \] (4)

Where \( I_i \) is the moment of inertia of the armature, \( D_i \) is the viscous damping coefficient, \( \theta_i \) is the rotation angle of mover, \( T_s \) and \( T_m \) are the friction torque and the torque acting on the armature, and \( i \) is the rotation axis of the mover (4).

4. Results and Discussion
Figs. 3 and 4 show the computed and measured rotation angles of X-, Y- and Z-axes, when the mover is operated to rotate in X-axis. As can be seen, the computed waveforms of Z-axis is a little different from the measurement because of low resolution capability of the angular velocity sensor and arithmetic processing unit of DSP control system, however, it is found that the interference of X-axis operation on other axes motion.

Discretization data is as follows. Numbers of tetrahedron element, edge element, and nodes are 647,577, 758,938 and 110,950, respectively. In addition the CPU time is about 20 hours (Number of steps: 240). In the final paper, the interference between other axes will be also discussed.
Study on a Simple Method for Controlling the Engine Output Power of Hybrid Powered Railway Vehicles with Electric Double Layer Capacitors

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Keywords: hybrid powered railway vehicle, electrical double layer capacitor (EDLC), energy storage, energy management

This paper presents a simple and energy-saving method for controlling hybrid powered railway vehicles that run on rural non-electrified railway lines and have diesel engine and electrical double layer capacitors (EDLCs). A schematic diagram of the hybrid traction system is shown in Fig. 1.

A basic idea proposed in this study is that EDLCs supply and absorb the kinetic energy of the vehicle and the engine output compensates the energy loss with the vehicle running. Thus, the energy loss is not taken into consideration while expressing the EDLC voltage reference (equation 1); energy loss is considered when the engine is in operating mode.

\[
V_{\text{ref}} = \sqrt{\frac{1}{2} CV^2_c - \frac{1}{2} Mt_v^2 \frac{v_t}{t}}
\]

\[C: \text{EDLC capacity, } V_c: \text{initial voltage of EDLC, } M: \text{mass of vehicle, } v_t: \text{vehicle speed}\]

A block diagram of the engine-output control system is shown in Fig. 2. If the inverter input power \(P_{\text{inv}}\) (load power) is greater than the threshold power \(P_{\text{th}}\), the engine output is controlled according to EDLC voltage error \(\Delta V_c\) (Fig. 3). Furthermore, when the engine output mode changes, hysteresis is induced so that chattering can be prevented (Fig. 4).

The proposed method is examined by performing numerical simulations for various values of engine operation time, load, and grade section. The results of this study reveal the relationship between the capacitance of the EDLCs and the fuel consumption, as shown in Fig. 5. Using this proposed control methods, excessive charging of the EDLCs can be avoided. The results of this study are expected to expedite the development of energy-saving railway vehicles for non-electrified railway lines.

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Fig. 1. Schematic diagram of the hybrid traction system

Fig. 2. Block diagram of an engine output control system

Fig. 3. Feed-forward engine output pattern

Fig. 4. Feed-back control rule of the engine output based on EDLC voltage error

Fig. 5. Relationship between EDLC capacitance and fuel consumption