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PART A: ENGINEERING AND INNOVATION

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Design and Implementation of a 300A Modular Welding Inverter

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Abstract

Welding machines are one of the most important application areas of power electronics. Controlling the fast dynamics of these machines while keeping the efficiency high is a challenging task. Several topologies and control methods have been proposed in the literature. This paper presents a modular structure for a 9.6 kW welding inverter. The design process is explained in detail. Simulation and experimental results are provided to show that the proposed system can be a viable solution.

1. INTRODUCTION

Welding is an important industrial application area of power electronics. While it was dominated by transformer-based designs in the past, the situation has changed dramatically in the last two decades. Nowadays the situation is other way around since the raw materials such as steel and copper cost more now, power electronic semiconductors are cheaper and more readily available, and finally digital controllers can easily handle difficult tasks [1-2]. With the advent of semiconductors, the switching frequencies keep increasing causing reduction in the size of welding machines. However, increased frequencies also increase the switching losses and radiated EMI. There are papers in the literature suggesting different methods to alleviate these problems. One of the proposed solutions is to use modular systems. Modular AC-DC power converter structures with three-wire and four-wire were compared in [3]. It was concluded that the prior one has better power factor correction and harmonic content. The proposed structure utilized modified buck converters. Power factor correction stage is a requirement now in many countries. A PFC phase modulated resonant transition converter is presented in [4].

Resonant mode converters are widely used to reduce the switching losses [5]. The problem with resonant mode is that the current peaks are very high and the control is more complicated. Most of the welding inverters have two secondary windings. A topology with two current-doubler rectifiers proposed in [6]. The proposed topology has reduced conduction losses due to the lower inductor current, at the cost of increased size and cost. A novel method is proposed in [7] to control the bus voltage and to improve the power factor by utilizing pulsed currents.

This paper presents the design and implementation of a 300 A, 9.6 kW output welding inverter with modular structures. Each module has a dual-forward converter as these converters provide a safe and simple operation in terms of magnetic saturation and switching. In order to reduce the switch voltages, the primary terminals of the two transformers are connected in series while the secondary terminals are connected in parallel to share the load current. A closed loop controller is designed to keep the load current constant.

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The design steps of the converter power stage are described in Section 2. Both power and control designs are explained. Section 3 and 4 give the simulation and experimental results.

2. CONVERTER DESIGN

Modern welding machines utilize power electronic converters. Half-bridge, dual forward or full bridge converters are used depending on the power level. Some manufacturers prefer to use resonant mode operation for reduced losses at the cost of more complicated design. In this work dual forward converter has been used. The advantage of these converters is that the two switches are turned on and off simultaneously reducing the complexity of gate drives, and that the flux resetting of the transformer is achieved automatically. On the other hand, the flux of the transformer is unidirectional and this causes the transformer to be larger. The topology selected for this application is shown in Figure 1. As seen at the figure, there are two dual-forward converters with the inputs connected in series and the outputs connected in parallel. This structure allows the use of lower voltage MOSFETS and thus increased switching frequencies [8]. Other advantages are that the transformer turns ratios can be decreased, and the system can be designed for higher input voltages (i.e. operating from three-phase input).

Both converters operate in-phase, reflecting half of the bus voltage to their secondary windings when the switches are on. Energy is transferred to the load through the forward biased diodes. The maximum possible value of the duty cycle ratio is 50%, and when the switches are turned off the energy transfer seizes. The magnetizing current flows through the diodes of the primary resetting the flux before the end of the period. Meanwhile, the load current flows through the freewheeling diodes at the secondary windings of each converter.

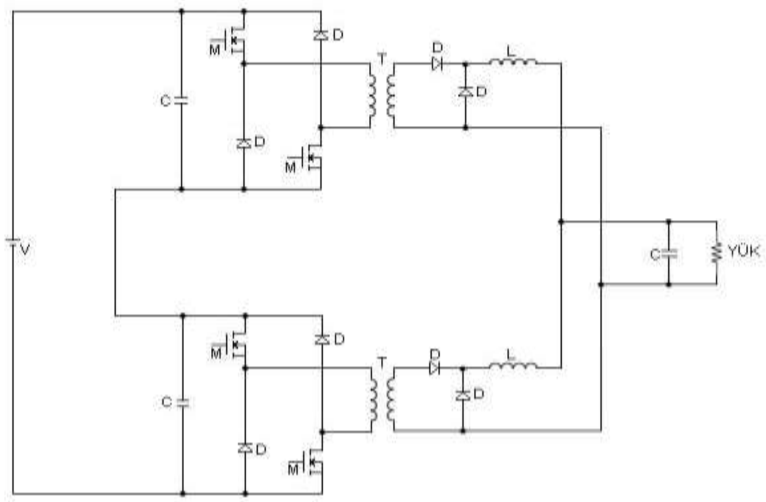

Figure 1. *Series-Input Parallel-Output connected dual forward converter structure*

Due to the parallel secondary structure, the load current is equal to the sum of the two transformer secondary currents. If all elements are identical and the switching is balanced, these currents are equal.

In the following sub-sections, the design steps of the converter are described for a 300 A welder. The supply is a three-phase 50 Hz AC source. The switching frequency is selected as 50 kHz, large enough to reduce the size and low enough for acceptable power losses.

2.1. Design of the Power Stage

The output voltage of the welding machine where the converter will be used and thus the lowest output power is defined by the international standard EN60974-1. Accordingly, the output voltage equation for a welding current of $I_W = 300A$ is found as $V_{arc} = I_W \times 0{,}04 + 20 = 32\ V$. This means that the welding power is 9.6 kW.

Considering the secondary rectifier voltage drop (1 V) and output shock and transmission drops (approximately 2 V), the lowest output voltage value in the transformer secondary side is calculated as 35 V. The power to be transferred to the secondary should be $P_S = 300 \times 35 = 10.5$ kW. Based on these values the design parameters for each transformer are given in Table I.

Thickness of conductive skin at 50 kHz is $\varepsilon = 66.2 \div \sqrt{50000} = 0.3$. 2ε thick foil conductors with a much higher filling ratio have been used for the windings. Core selection is realized based on the following equation;

$$W_a A_c = P_o J 10^4 / (4\eta\, B f K) \quad (1)$$

Table 1. *Design Data*

Minimum dc bus voltage	203 V
Maximum dc voltage	270 V
Output power	5250 W
Output voltage	50 V
Output current	150 A
Regulation	0.5%
Targeted efficiency	95%
Maximum duty cycle ratio	47%

where $W_a A_c$ is the area product (m^4), W_a is the window area, A_c is the core cross-section area, J is the current carrying capacity (A/m²), P_o is the power, B is the magnetic flux (Wb/m²), f is the switching frequency, K is the filling coefficient, and η is the efficiency. If $J = 2.5\ A/mm^2$ and $K = 0.2$ are chosen the area product ($W_a A_c$) is found to be $25.58\ cm^4$. EE 6527 of Cosmo Ferrites has been selected as the core. The properties of the core are listed in Table II.

Table 2. *Properties of the selected core*

Magnetic material	CF139	Core cross-section area (cm²)	5.3
Magnetic line length (mm)	147	Volume (mm³)	78200
Window height (cm)	1.21	A_L (nH)	8100
Window section (cm²)	5.4	Average lap length (cm)	14
Area product (cm⁴)	28.6		

Turn number of the primary winding can be calculated by using the following equation.

$$N_p = \frac{V_{in\,(\min)} d_{(max)}}{f A_c\, \Delta B} \quad (2)$$

If the saturation level is chosen as $\Delta B = 0.3T$, the turn number is found to be 12 for the given data. Transformer conversion rate is found as follows:

$$n = \frac{N_p}{N_s} = \frac{V_{in\,(\text{nominal})} * d_{(max)}}{V_{out}} = \frac{270 \times 0.47}{50} = 2.5$$

Then N_s is found as 4.8 and it is rounded up to 5 turns, changing the turns ratio to 2.4. Based on these numbers the primary and secondary coil inductance values are calculated as 1.17 mH and 202.5 µH. The transformer has been wound with sandwich technique as primary/2-secondary-primary/2 as shown in Fig. 2. Nominal duty cycle value is found as 0.32 from the following equation.

$$d = nV_o / V_i^{nom} \quad (3)$$

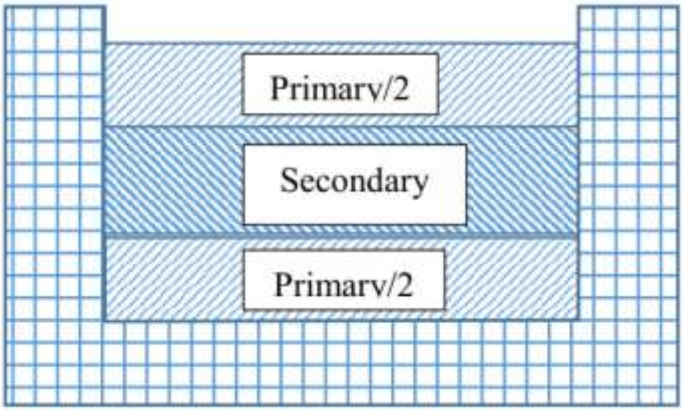

Figure 2. *Sandwich winding structure of the transformer*

The extreme values are found by using the minimum and maximum input voltages as 0.22 and 0.38. Based on these values the primary and secondary maximum rms currents are found as 38.5 and 61.6 A, respectively. Copper folio conductors have been used in the transformer. The thickness of the sheet is 0.33 mm for the primary. Two folio layers, each with a thickness of 0.3 mm, have been used in the secondary, with a layer of isolation in between.

Average length of turn for the primary is 14 cm. Therefore, the conductor length is 168 cm yielding 2.73 mΩ primary winding resistance and 4.88 W copper loss. Similar calculations result in 70 cm conductor length, 500.7 μΩ conductor resistance and 4.66 W power loss. Total copper loss is 9.54 W and as a result the regulation is

$$\alpha = \mathrm{P}_{copper}/\mathrm{P}_o = 0.18\% \qquad (4)$$

which is better than the specified design value.

The core loss data of the core is given as 600 kW/m^3 in the data sheet for 50 kHz. Therefore, the core loss is 47 W, making the total power loss is around 57 W and the efficiency of the transformer is around 99%. The switch selection has been made as 650 V, 40 A FGH40N60UFD IGBT devices of Fairchild company. Two of these devices were paralleled for each switch. The switching energy of one device is given as 1.89 mJ at 400 V. Considering the operation voltage of the converters in this application is around 250 V, this energy can be scaled to 1.18 mJ. At 50 kHz switching frequency the switching loss is calculated as 59.1 W per switch (two devices in parallel). As there are two of them in one bridge and there are two bridges, total switching loss is 236.4 W. The on-state voltage of the devices is around 2.2 V, and with the 62.5 A primary current and 0.32 duty cycle ratio the conduction loss is around 44 W per switch, totaling to 176 W for the converters.

The flux-reset diodes have been selected as 600 V, 30 A STTH30R06 devices of ST. These devices have 1.1 V forward voltage drops. Considering that they carry only the magnetizing inductance, their power loss has not been calculated.

On the secondary diode selection was made as 60 A, 300 V ultrafast diodes FFA60UP30DN of Fairchild. These are modules including two diodes. Two of these modules are connected in parallel for the forward diode, and three of them connected in parallel for the freewheeling diode. Each diode has 1.5 V drop. This means at 150 A, there is a power loss of 225W total in each converter module. Since there are two secondary modules, total conduction loss is 450 W. The reverse recovery loss of these diodes are negligible. All the power loss values are summarized in Table III. The overall efficiency is estimated to be around 90.8%.

Table 3. *Power losses of the converter*

Transformer Loss (W)	114
IGBT Switching Loss (W)	236
IGBT Conduction Loss (W)	176
Secondary Diode Loss (W)	450
Total Loss (W)	976
Efficiency (%)	90.8

2.2. Controller Design

The feedback control design for the converters is described in this sub-section. The function of the controller is to keep the welding current constant and therefore a current controller needs to be designed. The controller structure is shown in Fig. 3.

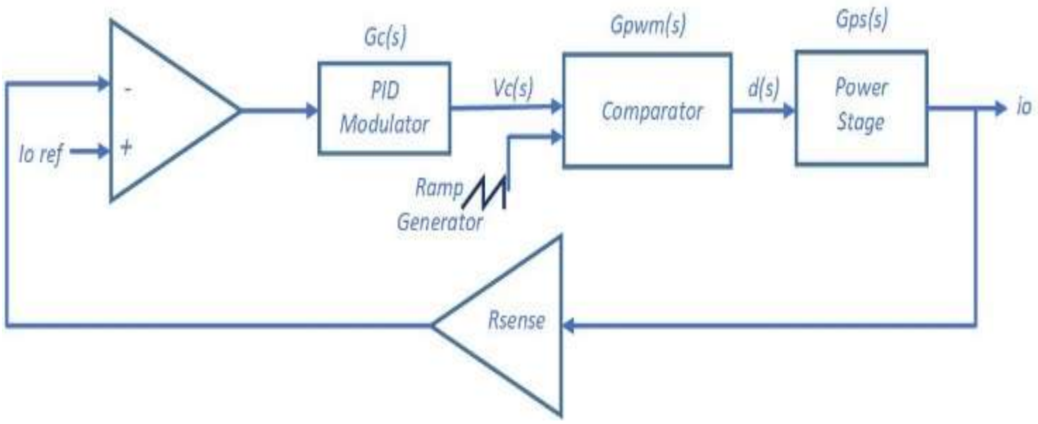

Figure 2. *Current control feedback structure*

The current is sensed by a sense resistor and fed back. The open loop transfer function is found as follows:

$$G(s) = G_c(s)G_{pwm}(s)G_{ps}(s) \quad (5)$$

In (5), $G_c(s)$ is the controller transfer function, $G_{pwm}(s)$ is the transfer function of the PWM block, and $G_{ps}(s)$ is the power stage transfer function. These functions are defined as follows:

$$G_c(s) = K_p + K_i/s \quad (6)$$
$$G_{pwm}(s) = d(s)/V_{sawtooth} \quad (7)$$
$$G_{ps}(s) = \frac{1}{n}\frac{1}{s^2LC + s\frac{L}{R} + 1} \quad (8)$$

Calculations for a stable control system yield $K_p = 6$ and $K_I = 16504$. The capacitor at the output is very small and could be ignored, reducing the system order to one.

3. SIMULATION RESULTS

The converter whose schematic is shown in Fig. 4 was simulated in LTSpice with the closed loop controller. In the simulation, a 540 V DC source is used at the input. 50 kHz switching pulses are sent to the switches of the two converters simultaneously. A resistor is connected as the load. The average value of the load voltage is expected to be approximately 32 V while the average value of the load current is expected to be approximately 300 A. As shown in Fig. 5, the currents through each inductors are 150A. In order to show the effectiveness of the controller, the load is decreased 50% after the steady state is reached. Fig. 6 shows the response.

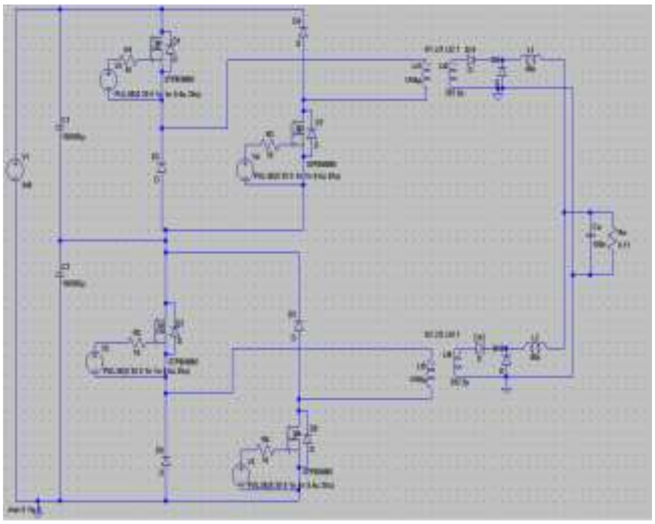

Figure 4. *Simulated converter structure*

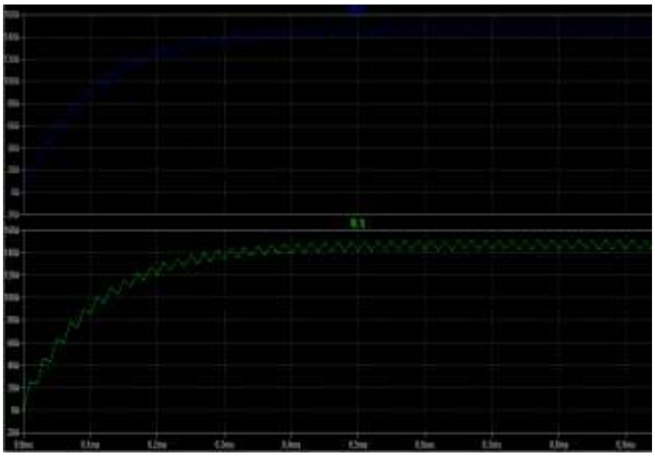

Figure 5. *Inductor currents*

A test was also performed to see the effect of unbalanced transformers. In the previous results the transformers have been assumed identical. Fig. 7 shows the response of the converter if the magnetizing inductance values (Lm) of the transformers are 966 mH and 1066 mH respectively. As seen on the results, the current is shared equally in spite of the differences.

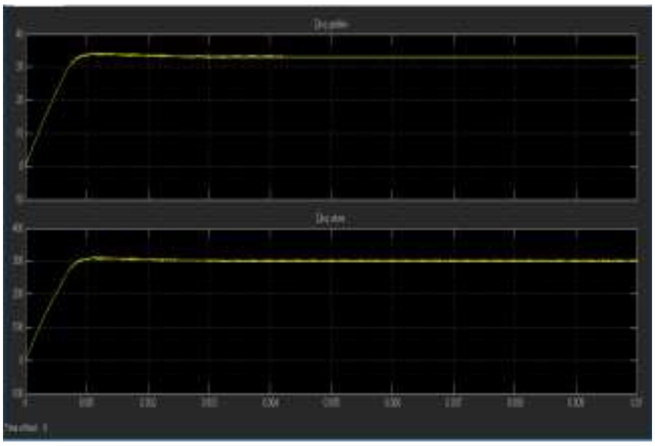

Figure 6*. Response to load change (upper trace: load voltage, lower trace: inductor current).*

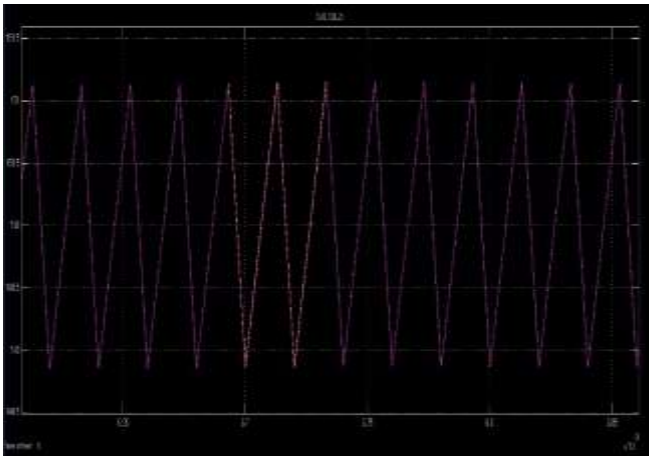

***Figure 7**. Non-identical transformer response to inductor currents*

4. EXPERIMENTAL RESULTS

The system was built and tested in the laboratory. The test set-up is shown in Fig. 8. Fig. 9 shows the operation at 300 A. Fig. 10 shows the current and voltage at MIG welding at 160 A load current. As seen from the graphs the converter response is as expected. The load current is shared between the two converters equally.

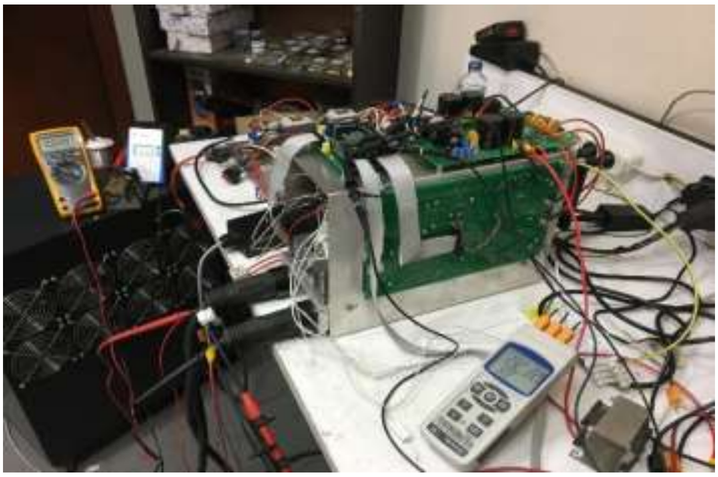

***Figure 8.** Experimental set-up*

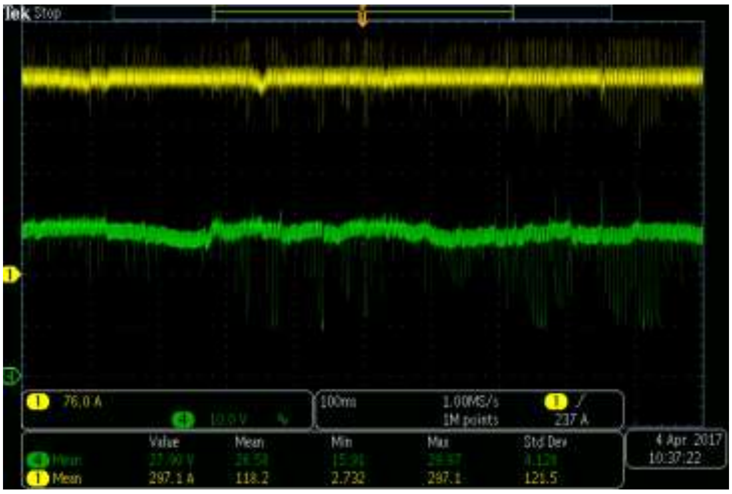

***Figure 9.** Current (Ch. 1, upper trace) and voltage (Ch.4, lower trace) at 300 A.*

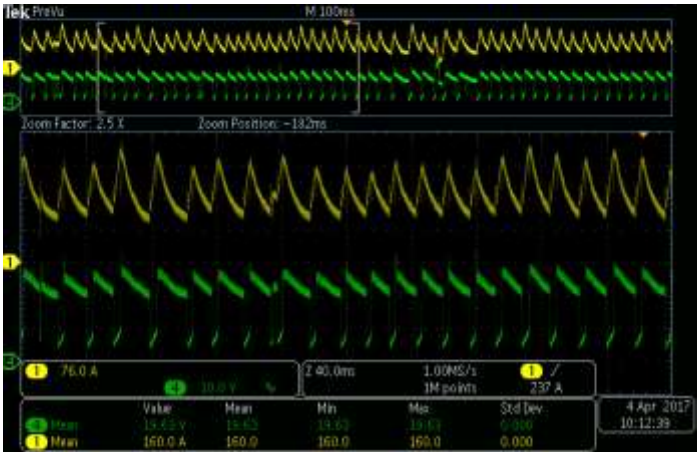

***Figure 10**. Current (Ch.1, lower trace) and the voltage (Ch. 4, upper trace); MIG operation at 160 A.*

5. CONCLUSION

The design and implementation of a welding inverter utilizing two identical modules of dual-forward converters are described. The modules are connected in series at the primary side and in parallel at the secondary side. This allows the use of lower voltage devices and higher switching frequencies. A controller design is also given to obtain constant welding current. Simulation and experimental results show that the controller performance is good, the welding current can be adjusted as desired, and the current is shared among the modules even when there is a mismatch between the modules.

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CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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PART A: ENGINEERING AND INNOVATION

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Design Optimisation of Rolling Element Bearings: A Literature Review

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Abstract

Optimisation is the process of finding the best design parameters that meet engineering needs and provides an inexpensive and flexible tool to define optimal designs to the industry prior to physical application. Engineers use empirical studies, statistical methods and optimisation techniques to evaluate research and determine the best design. In recent years, optimisation studies in the field of engineering has become an area of intensive work. The design optimisation of the bearings is one of these studies. In the design of bearings, there are various constraints such as geometric, kinematic, power, performance, long life and high reliability. An optimal design methodology is needed to perform these constraints collectively. In the literature, there are studies in which conventional and intelligent optimisation techniques are used for the optimisation of bearings. In this article, a source research is carried out, which includes the studies for the optimisation of bearings.

1. INTRODUCTION

Engineering design is an iterative process, which also addresses all parameters that may have an impact on target to achieve a particular goal. Mechanical design involves an optimisation process where designers always evaluate specific requirements (strength, deviation, weight, wear, corrosion, etc.) based on their needs [1]. Engineering design problems often have large scale and nonlinear or limited optimisation problems [2]. Design optimisation consists of a search field that contains appropriate solutions to specific objectives (objective functions) and a search process that contains optimisation methods [3]. Appropriate solutions are a set of all designs (design variables) characterized by all possible values of the design parameters. There are many applications where optimum design methods are useful in system design [4].

Conventional optimisation methods are commonly used in mechanical design problems. Conventional methods can use only a few design variables due to complexity and convergence problems. As the design parameters increase, the complexity increases and this makes it difficult to reach an optimum solution. They also have significant drawbacks, such as slow merger against local minimum (or maximum) problems [5]. In addition, as most of the mechanical design problems contain certain limitations, this makes it difficult to solve them with conventional optimisation algorithms [6]. An optimisation problem is too hard to be solved through conventional optimisation methods if it contains objective functions and constraints that are not expressed as explicit functions of design variables or is too complex to be manipulated [5,6]. Therefore, in recent years, intelligent optimisation methods have been used extensively in this field.

The main purpose of the design optimisation of rolling element bearings is to increase the service life and the reliability of the bearing. There are three critical parameters in the design of rolling element bearings. These are static load capacity (Cs), dynamic load capacity (Cd) and elastohydrodynamic minimum film

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thickness (H_{min}). The maximization of bearing performance is concerned with the maximization of these parameters. To obtain the optimum bearing design, the radial load capacity values (Cs and Cd) can be increased by optimizing the design, using optimisation techniques, whereby the radial forces and the ones acting on the conveying surface moving in the axial direction can be reduced.

In order to increase the working life of a bearing, the internal design variables of the bearing must be optimised. As bearings have a complex structure, there are many design variables and constraints in it. This is a phenomenon that makes it difficult to solve bearing design optimisation with conventional optimisation methods.

2. ROLLING ELEMENT BEARINGS

Rolling element bearings are used as an important component in most mechanical and aerospace engineering applications. Rollers or the rolling elements are machine elements that enable performance of a job by rolling element bearings between the inner and outer rings with at least friction and loss (Fig. 1).

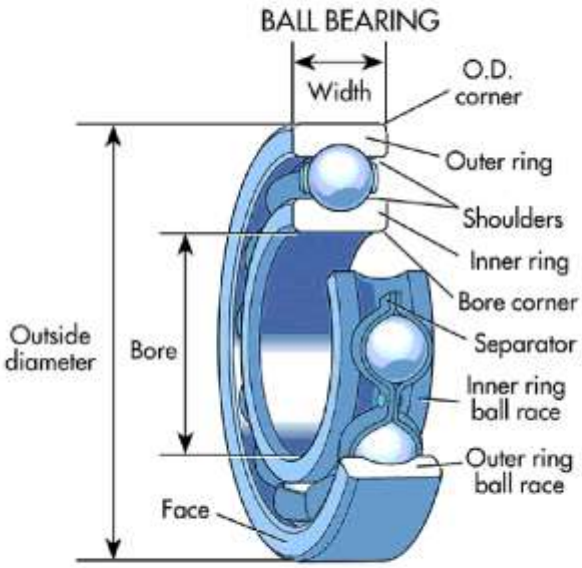

Figure 1. *Elements of a cylindrical rolling element bearing [7]*

The force is transmitted from the bearings to the shaft journal by the rolling elements between the two rings. The fact that coefficient of friction is low due to the bearings in rolling element bearings is the most significant advantage of rolling element bearings over sliding bearings. There are five types of rolling elements used in bearings with rolling elements. These are balls, cylindrical rollers, spherical rollers, tapered rollers and needle rollers.

The bearings can carry both radial loads and axial loads as shown in figure 1. Both loads can move together or separately. Rolling element bearings with cylindrical rollers have a larger contact with both slots therefore that they can handle large amounts of radial loads, however they are generally not preferred where the axial load is large. Slots of most of the rolling element bearings are fitted with separators. Separators are fitted to prevent friction, wear and rubbing of the rolling elements against each other [8]. Bearing elements have advantages in terms of cost, size, weight, bearing capacity, durability, accuracy and friction.

Rolling element bearings are subject to fatigue in high speed operations in all industrial sectors. Fatigue life is directly proportional to the dynamic capacity of the bearing. Therefore, the rolling element bearing design is a delicate process due to its non-linear and statistically ambiguous behaviour.

3. LITERATURE REVIEW

There are some studies in the literature that demonstrate the use of optimisation methods for different bearing types. The first aspect that stands out in the literature is the low number of studies conducted on this subject. It is possible to collect these studies under two main headings. These can be gathered under two headings namely, the studies carried out through conventional optimisation techniques and the studies carried out through intelligent optimisation techniques.

3.1. Studies Carried Out Using Conventional (Traditional) Optimisation Techniques

Conventional optimisation methods use a central node that bears the responsibility or coordination responsibility to decide on the optimal or near-optimal resolution of the problem. These methods are analytical and use differential equation techniques in finding optimum points. Because some practical problems include objective functions that are continuous and / or non- derivatised, conventional optimisation techniques have limited scopes in practical applications. However, a review carried out on calculation optimisation methods provides a basis for the development of most of the numerical optimisation techniques presented in the following sections.

Asimov's study on the optimisation of rolling element bearings is a pioneering endeavour in this field [9]. In this study, Asimov realised the optimum design of the length and diameter of a rolling element bearing that supported a certain load at a certain speed. In the study, the weighted sum of friction loss and shaft bending was minimized using the Newton- Raphson method.

Another pioneering study is the study of Seireg and Ezzat [10], which applies programming techniques for the development of bearing design systems. In the study, an automatic system was proposed for the selection of bearing length, radial clearance and average viscosity of the lubricant. The system optimises the performance of a hydrodynamic sliding bearing under certain speed and load.

Maday [11], Wylie and Maday identified design criteria to maximize the load bearing capacity of the bearing, using limited variable methods for calculating the variable to determine the optimum configuration of hydrodynamic bearings [11,12].

Seireg reviewed some examples for the use of optimisation techniques in the design of mechanical elements and systems [13]. These include gears, rolling element bearings, rotating disks, pressure vessels, shafts under bending and twisting, longitudinal impact beams as well as issues for elastic contact and load distribution.

Changsen described a design technique using numerical gradient-based optimisation technique for rolling element bearings [14]. He proposed five objective functions for the design of rolling element bearings: maximum fatigue life, maximum wear life, maximum static load ratio, minimum friction moment and minimum rotation rate. In the study, the concept of multi-purpose optimisation of rolling element bearings was proposed and only the basic concepts and solution techniques of the optimisation problem were presented without any illustration. Objective functions proposed for the optimisation of rolling element bearings were shown to be non-linear in conjunction with the geometric and kinematic constraints.

Hirani et al. introduced a design methodology for the design of engine journal bearings using various models developed by the same authors [15]. Selection of the length and diameter of the bearing cavity was described by means of limiting the minimum film thickness, maximum pressure and maximum temperature. A flowchart was shown for the effectiveness of the method proposed.

3.2 Studies Carried Out Using Intelligent Optimisation Methods

In recent years, some optimisation methods which are conceptually different from conventional mathematical programming techniques have been developed. These methods are labelled as modern or non-conventional optimisation methods. Most of these methods are inspired by biological structures and herd behaviours in nature. Intelligent optimisation methods that are intensively used are as follows:

- Genetic algorithms
- Simuluated annealing
- Particle swarm optimisation
- Ant colony optimisation
- Fuzzy optimisation

Most of these methods have been developed in recent years and have emerged as popular methods for solving complex engineering problems. Genetic algorithm (GA) is based on the principles of natural genetic and natural selection of candidate solutions to an optimisation problem [16]. Simulation of Annealing (SA) is based on heating of the solids and then slowly cooling them [17]. Both Genetic Algorithms and Simulation of Annealing are stochastic methods that are highly applicable to the solution of discrete optimisation problems that are highly likely to find the global minimum. Particle Swarm optimisation (PSO) is based on the behaviour of a live colony, such as a batch of insects, a flock of birds or a school of fish [18]. Ant colony optimisation (ACO) is an optimisation approach modelled on the actions of an ant colony [19]. In ACO, the ants were inspired by their ability to find the shortest path from food sources to their nests without using their eyesight. Fuzzy Logic is a form of logic where accuracy values of variables can be any real number between 0 and 1 [20]. It is an approach that deals with the concept of partial reality in which the value of the truth may vary between completely right and completely wrong.

In recent years, it is observed that there are increasing number of studies carried out on bearing design using the approaches mentioned here. The GA methods Choi and Yoon developed to determine the design parameters of an automotive wheel bearing in a type of double-row angular-ball bearing is one of them [21]. In the study, the design problem of rolling element bearings is seen as a limited optimisation problem. It is seen in the study that a wheel bearing unit optimally designed increased the system life without any violation of limitations.

Kalita et al., in their study carried out on multi-purpose optimisation for the design of bearings, made a weighed combination of purpose functions consisting of dynamic capacity, static capacity and minimum film thickness [22]. The multipurpose problem was transformed into a problem of scalar optimisation. Deterministic algorithms and stochastic algorithms were used in this study to solve the limited scalar optimisation problem. Internal penalty function method was used as the deterministic approach and Simulation of Annealing and Genetic Algorithms were used as the stochastic approaches.

Chakraborthy et. al. proposed a method that used Genetic Algorithm to solve problems that arise in designs based on the standard bearing tables of rolling element bearings and performance characteristics of bearings [23]. In the study, the design parameters used in conventional optimisation techniques were increased from three to five. In addition, a design model that took into account the fatigue life which was not taken into account in the tables was presented.

Gupta et al., optimised static capacity, dynamic capacity and the elastohydrodynamic minimum film thickness in bearings using multi-objective optimisations [24]. Dynamic and static capacities were discovered to be very sensitive to changes in the inner channel curvature coefficient.

Rao and Tiwari, identified a procedure to solve the classified, constrained, nonlinear optimisation problem for the design of rolling element bearings [25]. The mounting angle was derived from the design parameters. A total of ten design variables were considered in the study in which there were five design parameters. Problem was optimised in two stages. GA was used for optimisation. It was seen that dynamic capacity had been developed based on those listed in standards.

Rao and Tiwari developed a bearing design method through realistic constraints for single-purpose optimisation and with the help of Genetic Algorithm [26]. In the study, they discovered that optimised design parameters provided a better fatigue life than those listed in standard catalogues. They carried out a convergence study to ensure that optimised design of the local variables would not be affected by the local extremities (minimal and maximal).

A nonlinear constrained optimisation problem was proposed by Kumar et al. for the design of cylindrical rolling element bearings and a procedure was described for the solving of the optimisation problem [27]. In the design of cylindrical bearings, four geometric variables and five constraint constants were selected for optimisation of the basic dynamic capacity. Geometric constraints were formulated from the standard boundary dimensions in bearing standards. The input of the design problem was selected from the bearing standards and catalogues available for a designer. Using real coded genetic algorithms, the bearing design problem was optimised and the resulting bearing dynamic capacity was compared to the values in standard catalogues. A sensitivity analysis was performed to see the effect of manufacturing tolerances on design variables.

Bearing design problem was optimised by Kumar and Tiwari using genetic algorithms for the design of cylindrical rolling element bearings [28]. When optimised bearing dynamic capacity and fatigue life were compared to the data in standard catalogues, an improvement was noticed.

In the study of Wei and Chengzi, a problem that would extend the bearing life by reducing the bearing friction losses was considered [29]. The multi-purpose optimisation problem was solved using NSGA-II. While macro-geometries of the bearing (bore diameter, outside diameter and width) were considered as standard, non-standard internal geometry parameters were used. It was discovered that, when the rotational friction power loss was the same as the existing design, lifetime of the optimised design was 36 % longer than the existing design.

A non-linear constrained optimisation problem was formulated by Tiwari et al. for the design of tapered-roller bearings and a procedure was described for the resolution of the optimisation problem [30]. In the study, realistic constraints were formulated based on geometric, bearing standards and durability factors. Geometric constraints were formulated from the standard boundary dimensions in bearing standards. Design problem input was selected from the bearing standards and catalogues. Design optimisation problem was optimised using real coded genetic algorithms and related dynamic load capacity demonstrated improvements in fatigue life based on the standards given in the standard catalogues. A sensitivity analysis was carried out to observe the effect of manufacturing tolerances on design variables.
Waghore and Tiwari proposed a hybrid approach to optimise the dynamic capacity of bearings [31]. Non-linear optimisation formulation was resolved using Artificial Bee Colony Algorithm (ABCA), Differential Search Algorithm (DSA), Grid Search Method (GSM) and Hybrid Method (Combination of HM, ABCA / DSA and GSM). Sensitivity analysis was conducted to see the effects of tolerance on the design variables and the dynamic capacity. The dynamic capacity of the optimised bearings was found to be higher than those specified in the bearing catalogues.

Panda et al. addressed the fatigue life, which is an important problem in the design of rolling element bearings [32]. In the study, the dynamic load capacity of the radial rolling bearing was optimised using new constraints with Sort-Based Constraint Processing method. In addition, basic design variables were illustrated together with constraints. With the method developed, a stable bearing design with lower contact stresses was obtained. A hybrid algorithm consisting of PSO and TLBO was used in the study. The convergence rate was increased while the constraints were satisfied with the hybrid algorithm developed.

In the study carried out by Eugenio Dragoni, the internal dimensions of the tapered rolling element bearings were optimised for maximum dynamic capacity [33]. The bearing system discussed comprises of two identical bearings which are formed under any combination of radial and axial forces. It was shown that the basic rating life quadratically increased more when in the cylinder and that the aspect ratio of the cylinders increased to the sixth power of the pitch diameter of the cylinder set and decreased to the third power of the radial force applied.

Dynamic load capacity of rolling element bearings was optimised by Husain Bavasab Shaikh and Avinash Gulabrao Kamble using Jaya algorithm [34]. The effect of various design parameters on a specific response parameter was analysed. The results of the Jaya algorithm were compared to the values obtained from the genetic algorithm and the optimisation technique selected yielded better results than the genetic algorithm.

Jat and Tivari used NSGA-II approach in their study, in which they optimised fatigue and wear behaviour of spherical rolling element bearings [35]. In the study, in which multi-purpose optimisation approach was used, the purpose functions were dynamic load capacity and hydrodynamic film thickness. In the study, bearing life factor and specific film thickness increased compared to the existing design. In the sensitivity analysis performed to estimate the effect of the deviation of design variables on objective functions, the tolerances of three design variables and objective functions were shown. It was observed that the life of the bearing had increased through the optimisation method.

Teaching and Learning – Based Optimization (TLBO) was used by Dandagwhal and Kalyankar for the optimisation of the dynamic capacity of rolling element bearings, which is a new optimisation technique [36]. 9 design variables were considered for the selected problems. The results obtained were confirmed to be better than the standard catalogues and manuals. Therefore, it was demonstrated in this study that the performance optimisation proposed in bearing design was applicable.

4. CONCLUSION AND DISCUSSION

In this paper, a literature study was carried out on the necessity of design optimisation techniques on rolling element bearings. As the bearing industry was out of the scope of professional studies carried out in the field of optimisation in the past, only a few studies have been carried out on rolling element bearings. In the last two decades, however, a number of scientific studies have come to the forefront for optimal bearing design using different types of optimisation algorithm techniques. In this study, studies on optimum bearing design were evaluated.

It is seen that the studies made on the subject concentrate on high bearing capacities, low weight, low friction losses and high wear resistance in rolling element bearings. Conventional optimisation approaches were used in the earlier studies performed for this purpose. As some practical problems involve objective functions that are continuous and/or non-derivatised, conventional optimisation techniques do not allow the desired results to be achieved in optimum bearing design.

Intelligent optimisation techniques that have come up in the solution of engineering design problems over the last two decades draw attention as techniques that are solid, flexible, easy to solve, and that can be the best solution in a shorter time than other conventional techniques at the same time. As seen in this literature study, studies carried out on bearing optimisation in recent years have mainly focused on intelligent optimisation approaches. Many optimisation approaches were used for this purpose. Among the approaches used, GA stands out. However, studies on optimum bearing design have been carried out using other approaches, as well. When the studies in the literature are examined, even though better results are obtained in the studies carried out in intelligent optimisation techniques, more scientific studies are needed to be carried out on the optimal design of bearings.

CONFLICT OF INTEREST

No conflict of interest was declared by the authors

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