# Introduction

* Eski slip ringler, mekanik, brushless exciters +
* Bu eski çözümlerin kötülükleri +
* Şimdi WPT- IPT slip ringler (IPT’ye geçiş kötü) -
* Complexity-cost 🡺 additional converter +
* Proposed system +
* Eskiden motor / IPT ayrımı +
* Şimdi Gan 🡺 frekans, buraya Si, GaN resmi +
* Bu gelişmelerler birlikte single bridge
* Önerdiğimiz systemin avantajları, tablo koyalım karşılaştırma +
* Sistemde extra hardwre olmadan motor sürrüclere konulabileceği+
* Böylece şimdiki sistemlere mount edilebilme kolaylığı +
* Power ratinglerin karşılaştırlıması, motor, IPT less than 10 percent +
* Ama kötü yanlarıda var, IPT sistemleri verimleri yüksek ZVS falan, efficiency düşecek
* Paperi anlatalım, bitirelim

Slip rings are electromechanical devices to transfer electrical power from stationary to rotatory frames.

They are used in many applications such as electrical excited synchronous machines, solar wings, radar systems, etc.

In the past, mechanical slip rings, made of carbon brushes and copper plates, are used.

The carbon brushes rub the copper plates to make electrical contact during rotation.

Since mechanical friction causes physical corrosion, the system is not reliable and requires periodic maintenance.

Another type of slip ring is a brushless exciter, an electrical machine to transfer power to the rotatory side.

Although they reduce maintenance requirements and give a more reliable system than mechanical slip rings, brushless exciters need a larger volume. The power transfer capability depends on the system’s speed.

Nowadays, wireless power systems (WPT) are aforethought to replace with slip rings. The WPT systems give more reliable systems thanks to lack of physical connection. Besides, the power is transferred regardless of the system speed.

There are various WPT types, such as inductive power transfer (IPT), capacitive power transfer (CPT), microwave, etc.

Since IPT systems meet the various power level and distances, IPT based slip rings are commonly applied.

A mechanical and IPT based slip rings are shown in Fig. \ref{fig:general\_structur}-a and \ref{fig:general\_structur}-b.

As mentioned before, the reliability and maintenance issues are solved by the IPT system.

However, the IPT increases the system complexity and cost. As shown in Fig \ref{fig:general\_structur}-b, the IPT system needs an additional converter that generates high-frequency pulses.

The converter is connected to the same DC bus with the converter of the motor driver.

To reduce the system's complexity and cost, we propose that the IPT converter and motor driver be combined in a single converter shown in Fig. \ref{fig:general\_structur}-c.

In the past, it is hard to make the motor driver and IPT converters combine in a single converter since the switching frequencies of them are far away.

The converters of the motor driver operate at a low switching frequency (< 30 kHz), and the IPT’s converter operates at a high switching frequency (50 kHz < fsw < 100 kHz).

For the silicon-based transistors, the motor driver's switching frequency is restricted due to increasing driver losses.

Besides, the IPT is physically feasible above (50 Khz) since the IPT passive elements' size is inversely proportional to switching frequency.

Thus, it is hard for the system with Silicon (Si) based transistors to intersect that two operation frequencies on a single converter. Fig X shows the power rating-frequency relation of the Si devices. The power is not considered only IPT power, and it will be the combined power of the motor driver and IPT.

However, recent developments in semiconductor technology pave the way for an increase in the switching frequency, especially for a Silicon Carbide (SiC) or Gallium Nitride (GaN) based motor driver circuits.

Besides their main advantages like lower conduction losses, small package designs, better cooling performances, wide band-gap (WBG) devices are advantageous for their rapid switching transients.

Therefore, now, it is possible to apply a high switching frequency to the motor driver (as shown Fig X) so that the IPT and the motor driver can operate at the same switching frequency.

The basic representation of the proposed system is shown in Fig X. Thus, the HF converter of the IPT is removed, and the IPT and motor driver are combined in a single converter.

Table X shows the advantages and disadvantages of the proposed system over the rivals.

The proposed system meets the system requirements and solves the complexity and cost problem due to an additional HF converter. However, the system decreases the overall efficiency. In classical IPT, converters operate at zero voltage switching (ZVS) to reduce the switching losses. In a single converter, the ZVS requirements are not meet due to motor currents. Thus, the overall efficiency of a single converter is lower than a system with two separate converters.

Further, the power ratings of the IPT systems are less than 10 percent of the motor because the slip rings are used to transfer the power of field excitation or electronic loads such as surveillance cameras, radar and etc.

Then, the conventional motor driver can supply the IPT power by staying safe region to power ratings.

Hence, the elder slip rings can be replaced with the proposed system without changing the converters of

the motor drivers.

However, DC-Link capacitance requirements should be checked whether it meets the switching current or not since the IPT draws a high-frequency current. The DC-Link capacitance can be increases by considering the current and the voltage ripples of the bus voltage.

Although the proposed system can be implemented to various motor (including AC and DC) and IPTs, a separately excited direct current (DC) motor and series-series compensated IPT are used as a proof-of-concept in this paper.

The remaining part of the paper is organized as follows. In the second section, the proposed system is explained analytically. The third section states the design considerations easy-to-follow. In the fourth section, the decoupling of motor and IPT control will be revealed. The fifth section delivers the experimental results and a comparison between simulation results. In section sixth, a discussion part for the generalization of the proposed method for other types of motor and IPT will be investigated.

# System Proposal

* Proposed systemi gösterelim (figure, renkler ile ayrılsın) +
* FB converter VSC’den bahsedelim, parallelleme yapılabilidiğinden söz edelim +
* DC motor sürülecek, akım filtrelenecek, switching function, duty cyle göre harmonicler+
* IPT açıklamaları, co,l,copmpensation, phase shift aynı switching frequency +
* Aynı driver, aynı PWM ile sürdük. O zaman single yapıp parallelemizde bir sorun olmaz. Tek bir converterle koyabiliriz.

For the proposed system, the motor and IPT systems are connected parallel to a single full-bridge converter shown in Fig \ref{fig:proposed\_system\_H\_bridge}.

The full-bridge converter is a voltage source converter (VSC), which generates pulsating output voltage by pulse width modulation (PWM).

The converter can be used as a single combined converter of the motor driver and IPT if it provides the following statements.

* The loads’s (motor and IPT) currents do not affect the output voltage of the converter.
* The same switching function (PWM) is used to control power of the loads.
* The commutation between the loads does not affect the current of each load.

Firstly, VSC provides with the independent output voltage from the load currents while ignoring the parasitic line inductances. With the presence of the parasitic inductances, the voltage drops at DC Bus voltage decreases the output voltage.

The independent output voltage from load current can be achieved by proper layout (minimizing parasitic inductances) and using enough DC-Bus capacitance. Thus, the first requirement of combined converter is achieved.

Secondly, the converter is employed to drive a DC motor. Since the inductance of the motor filters out the current harmonics, DC voltage is adjusted to control the motor's power.

A switching function of switching frequency(fs) and duty cycle(D), given in (\ref{eq:Switching\_Fourier}), is used to create the desired DC voltage.

However, the output voltage consist of switching harmonics in addition to DC, shown in Fig .\ref{fig:dutycycle\_harmonics} as a function of the duty cycle.

As a brief explanation of IPT, the power is transferred by magnetic coupling between the transmitter(Tx) and the receiver(Rx) coil.

The coils are loosely coupled coils with high leakage inductances which adversely affects the power factor.

Thus, compensation circuits are used to avoid the effect of leakage inductance. There are various compensation methods in the literature: two-element (SS, SP, PP, PS) and hybrid compensation (LLC, LCC). For our design, SS-IPT is chosen because the resonant frequency does not depend on the load and coupling.

In a typical IPT system, symmetrical PWM is employed, and the fundamental harmonic approach (FHA) can be applied in SS-IPT since the odd harmonics are filtered out. For symmetrical PWM, the fundamental harmonic is controlled by phase-shift and frequency control.

Furthermore, the asymmetrical PWM is also used in IPT systems. In asymmetrical PWM, the multiple harmonic analysis (MHA) is used to consider the switching harmonics. The power of IPT is adjusted by duty cycle and frequency.

The switching function, given in (X), creates asymmetrical PWM which can control both motor and IPT. Then, the second requirement of combined converter is achieved.

Thirdly, the motor and IPT operation frequency is far away. The motor operates at DC and it behaves like a low pass filter, have a high-impedance at switching harmonics. Besides, the IPT operated at switching function and it behaves like a band-pass filter which have a low-impedance near the switching function. The circulation current between the IPT and the motor does not occur so that the third requirement of combined converter is achieved.

As a result, a combined single converter of the IPT and the motor driver is proposed for a voltage source full-bridge converter (VSFBC).

# System Design

The proposed system aims that slip rings are implemented in a conventional motor driver without using any additional hardware. Hence, the converters of motor drivers are used as both motor drivers and IPT converters. In this section, an IPT system will be designed for a specific DC motor driver. The input and output parameters of the system, which is considered in the design stage, is given in Table \ref{tab:system\_parameter}.

# Motor and driver

The motor and the driver setup include a separately excited DC machine and a GaN based full-bridge converter shown in Fig X. The DC machine has a 220~V 2500~W of rated power under nominal speed, 1500~rpm. The full-bridge converter consists of two GaN based half-bridge boards on which a device paralleling is applied as details described in \cite{Karakaya2021}. The converter is rated at 5.4~kW with 450~kHz switching frequency and has a power density of 5.24~kW/$l$.

In this paper, the input voltage is 100~V due to voltage rating of the power supply in the laboratory. Hence, the motor is operated at power of 500~W with 100~V DC-Bus. The motor parameters are given in the Table X.

# Switching and duty cycle Range

Although the maximum switching frequency of the converter is given 450~kHz, there are some consideration to select the switching frequency. Increasing switching frequency goes up the switching losses of the driver, reduces the lifetime of the driver, damages the insulation of the windings, causes EMI noises. Besides, decreasing switching frequency increases the current and the torque ripples of the motor which depend on electrical time constant of the motor.

The minimum switching frequency is 1~kHz because the motor, used in the paper, have higher electrical time constant. Moreover, the maximum switching frequency is selected as 100~kHz by considering both the isolation of windings and switching losses of the driver.

Furthermore, a maximum and minimum duty cycle should be selected to determines the input voltage range which is utilized by motor and IPT. As can be seen in Fig X, the input voltage of DC motor changes the sign at 0.5 duty cycle, that determines the rotation direction. Besides, the input voltage of IPT (at switching frequency) is symmetrical about 0.5 duty cycle and the input voltage decreases while approaching the duty cycle of 0 and 1. To use IPT in a constant power for any operation of the motor, the duty cycle of the driver is restricted due to switching harmonics are eliminated while duty is coming close to 0 and 1. The duty cycle range is selected as 0.15-0.85 shown in Fig X, yellow region and the IPT design will be made with the restrictions.

The duty cycle range is selected as 0.15-0.85 shown in Fig X, yellow region. For the duty cycle and 100~V DC-Bus voltage, the input voltage of IPT fluctuates between 40V\_rms and 90 V\_rms.

# IPT DESIGN

The motor driver duty cycle is selected between 0.15 and 0.85, and the operation frequency range is chosen between 1kHz and 100kHz.The IPT is designed concerning these restrictions.

The selection of the resonant frequency is important.

Increasing frequency reduces the size of the passive elements but increases the coil losses. In this paper, the resonant frequency is selected 65~kHz since the converter switching frequency is up to 100kHz. The input voltage is also changing concerning to duty cycle. The voltage is between $ \mathrm{40 V\_{RMS} }$ and $ \mathrm{90 V\_{RMS} }$ with 100V Bus voltage and 0.15-0.85 duty cycle range.

The output voltage and power of the IPTs have already been decided $ \mathrm{20 V\_{RMS} }$ and 50 W, which is 10% of the motor rated power.

A systematical design for SS-IPT, taken from \cite{aditya}, will be applied.

Firstly, the load resistance is found by using X.

Secondly, the secondary inductance can be calculated by using (). The quality factor (Qs) is selected between 1-10 in the literature. The Qs increases the secondary inductances but decreases the primary inductance for the other parameter’s constant.

Thirdly, the mutual inductance can be calculated by using (). In this point, we should select the input voltage, which actually changes to duty cycle. In the design, the voltage gain at resonant frequency is considered and the gain can decrease by frequency. Then, we select the minimum voltage in the design parameters because the power con be kept constant for much bigger voltages by frequency control.

Fourthly, the Tx inductance is found by using (). The coupling coefficient is between 0 and 1.

The k decreases the Tx inductances but decreases the primary inductance for the other parameter’s constant.

Finally, the capacitance values can be achieved by using ().

The coupling factor and Quality factor affects the IPT characteristic in doubly compensated circuit. A bifurcation phenomenon can occur concerning the selections. The bifurcation phenomenon is called pole-splitting, which creates three zero-phase angles rather than one zero-phase angle. In a classic way, the switching losses are reduced by zero voltage switching (ZVS) by operating in the inductive region of the IPT.

An IPT guarantees the inductive operation above the resonant frequency without bifurcation but does not guarantees it with bifurcation.

However, ZVS is not guaranteed by the bifurcation-free of the IPT due to an additional motor current in our case.

Moreover, the choice of the quality factor and the coupling determines the gain concerning the frequency. It is also important because the asymmetrical PWM, having second harmonics, can affect the IPT power. As can be shown in Fig X, the second harmonic is also changing as duty cycle and the elimination of second harmonic provides only switching fundamental harmonics control.

The change on Tx, Rx and mutual inductances as a function of coupling coefficient and quality factor are shown in Fig X a and b. In addition, the gain-frequency characteristics for a various coupling and quality factor is given in Fig X.

In this paper, the quality factor and coupling coefficient are selected as 0.40 and 2.5 by considering the size of Tx and Rx inductances and the gain of second harmonics, The design is pointed in Fig X.

The design parameters selection changes the control range of IPT. The effect will be argued later.

# Design consideration

In this section, we investigate the effect of IPT on the motor and converter.

Firstly, the impedance modelling is established to analyze the commutation between IPT and motor.

Secondly, the effect of IPT on DC-link current of the converter is examined. Finally, the effect of IPT on the efficiency of the converter is argued.

Fig X shows the basic impedance circuit of the combined IPT and motor system. The converter is modeled as a voltage source. The input impedance of the motor and IPT showed in Fig X. At a steady-state, the motor and IPT are decoupled concerning the operating frequencies. They behave like open-circuit at each other's operation frequency.

We investigate the open and short circuit conditions of the IPT. The open and short circuit conditions are shown in Fig X. The motor is not affected by these conditions.

Also, transient conditions are investigated by using a simplified model. The transients of IPT and motor are shown in Fig X.

# Capacitors

Unlike a conventional motor driver, the addition of the IPT current on the motor driver also increases the stress of the DC-Link.

Hence, the system may require a modification on the DC-Link capacitor due to the high frequency IPT current.

A high capacitance makes the system larger, and a low capacitance causes DC-bus voltage to fluctuate due to the high frequency current of an IPT.

The basic circuit used in the analysis is shown in Fig. 7. The current, supplied by DC-link capacitors, is expressed in X.

The motor and IPT currents are shown in (5). The switching harmonics of the motor current are ignored, and FHA is applied to IPT current.

As can be seen in (6) and (7), the DC-Link current depends on the load torque of the motor, duty cycle, operation frequency, Tx current magnitude, and phases.

# Scenerio

We investigate a scenario to investigate the capacitor current. The calculations are made by analytically

In this scenario, the motor current increases with the duty cycle linearly and draws the maximum power at the maximum duty cycle 0.85. The DC-Link capacitor current from motor is shown in Fig. 8-a. Also, the Tx current of the IPT is kept constant. For increasing the duty cycle from 0.5 to 0.85, the input voltage decreases. For the constant power, it is expected the Tx current increases. However, Also, power factor changes and Tx current can be taken as constant with zero phase to observe the effect on the DC-Link. The DC-Link capacitor current from IPT is shown in Fig. 8-a.

It is observed that the fundamental of the capacitor current is doubled for a higher duty cycle. Then the DC-Link capacitance should be modified to keep the DC-Bus voltage change the same as the only motor, as shown in (8).

# Efficiency

In this section, the losses of the driver are investigated.

The driver losses can be divided into two main parts, which are conduction and switching.

The losses are calculated for rated current values of both motor and IPT.

In typical IPT based slip ring system, the HF converter of IPT operates at inductive region to make ZVS. Then, the switching losses of the converter decreases and the dominant losses of the converter is conduction losses. However, combined system, ZVS is not guaranteed due to motor current so that the overall efficiency of the system decreases. Moreover, operation frequency of IPT affect the losses due to not unity the power factor, which increases the losses.

Fig X shows that the loss distribution of a conventional and proposed system.

# Duty cycle limitation

In a DC motor, the duty cycle is constant if a steady-state condition is thought. At this point, the motor duty cycle is limited by IPT because the power of IPT converges to zero by approaching duty cycles 0 or 1. However, the limitation is valid for DC motor. For the AC motor, PWM is applied to create a sinusoidal or trapezoidal waveform hence a duty cycle is changed periodically at steady state with respect to modulation index. Then, the power of IPT does not converges to 0 for any operation.

# Power Ratings

In this paper, we design an 50W IPT systems for 500W motor at 100V Bus voltage. For this design, the current rating of IPT are close to rating current of the motor. However, the design is also used for 220V Bus voltage, which is rated voltage of the motor. At this point, the output voltages and Tx current of IPT stay the same and the power rating of IPT increases. At the 220V bus voltage, the current rating of IPT are becoming less than the motor current. Then, the DC-Link modification and efficiency could be re-investigated.

# Conclusion

This paper proposed a novel system that combines IPT and motor in a single converter. Unlike conventional systems, the system removes the additional converter of the IPT. It reduces the complexity and cost of the systems. However, the overall efficiency of the proposed system is lesser than conventional two separate converter due to missing ZVS. Moreover, the proposed system provides a conventional motor driver to be applied with only small modification of DC-Link capacitance. Although there is no additional hardware, the control of the motor driver could be limited due to IPT concerning motor types. In this paper, an IPT is designed for DC motor and driver as proof-of-concept. The proposed system will be expanded for various types of motors and drivers.

# Abstract