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An Overview On Wireless Power Transfer For Electric Vehicles: Technology And Its Status

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Abstract: Electric Vehicles (Evs) Will Be One Of The Possible Solution Future Transports, Which Is More Essential Due To The Environmental Concerns And Depletion Of Oil Resources. Conversely, The Technology And Facilities For Charging Is Lacking, And Also Possibility For The Owners Of The Cars To Forget To Plug In. Wireless Charging (WC) Of Electric Vehicles Using The Inductive Resonance Principle, Can Provide Automatic, Secured, And Effortless Charging Solution For Evs. WC Systems Paved A Path For On The Move Charging Called As Dynamic Charging, Which Helps To Increase The Mileage/Charge, Reduce The Battery Size And Hence Vehicle Weight And Cost. In This Paper, Techniques Available For WC, Inductive Coupled Charging And Issues, Organizations & Institutes Involved In The WC Research And Their Status Are Reviewed.

***Keywords:** Wireless Power Transfer, Inductive Power Transfer, Resonant Magnetic Induction, Microwave/RF Radiation, Electric Vehicle Charging, On-The-Go-Charging*

1. INTRODUCTION

Electrifying The Road Transportation Is The One Of The Prime Challenge The World Has At Present Because Of Issues Due To The IC Engine Based Transportation System, Such As I) Depletion Of Oil And Gas, Ii) Environmental Pollution, And Iii) Global Warming Etc. Oil Will Exist Up To 2060 If The Present Consumption Trend Is Continued. Hence It Is Necessary To Find Alternate Fuel Or Energy Sources For Transportation. One Of The Alternate Is Battery Vehicles Which Are Called As Electric Vehicles (Evs). In 2018, Road Transportation Demanded 55 % Of Total Oil Consumption Of The World And Contributed 24 % Of Global CO_2 Emissions[1, 2]. India's Crude Oil Imports Account For Rs 4.7 Lakh Crores In 2016-17. Introduction Of Electric Vehicles And Renewable Energy Based Power Generation Will Help Lower This Cost. The NDA Government Set The Goal That *India To Be 100% Electric Vehicle Nation By The Year 2030***.** The National Electric Mobility Mission Plan (NEMMP) Of India Targets 7 Million Electric And Hybrid Vehicles By 2020 Itself[3].

Electrification Of Trains Has Been Carried Out In Many Countries For The Past Few Decades. Trains Are Running On Fixed Lines, Hence Transfer Of Power Is Easy Through Pantograph Sliders. But For The Vehicles Moving On The Roads, Getting Electricity Is A Bigger

Challenge. The Technology For This Purpose Has To Grow A Long Way. High Power Density Battery Banks, Power Converter Technology For Charging Are Necessary For Evs.

Significant Challenges Of Wireless Charging Of Evs Are I) Larger Air-Gaps Between Receiver And Transmitter, Ii) Greater Power Levels, Iii) Lower System Losses To Meet Efficiency Requirements, And Interoperable Systems From Different Manufacturers Over The Full Range Of Operation[4].

Even Though Evs Are Having The Limitations Such As Longer Battery Charging Time, Limited Mileage Per Charge, Life Time Of Battery, And High Cost Of The Evs, They Are The Scope For Future Transportation Because They Offer The Advantages Of I) Alternate Solution For Depleting Oil Sources Ii) Emission Less Operation Iii) Noiseless Operation Iv) Environment Friendly. Charging Methods Of Evs Are Classified Into Two Categories, Namely I) Wired Charging (For Plug-In Electric Vehicles (Pevs)) And Ii) Wireless Power Transfer (WPT). Wired Charging Of Evs Has Various Shortcomings For Instance, The Need Of Charger And Connecting Cable, The Size And Weight Of The Charger, Isolation Of On-Board Electronics, Safety Issues While Their Operation In The Rain And Snow.

Electric Power Or Communication Signals Can Be Transferred Though Magnetic Field. As In Transformers And Induction Motors, Effective Coupling Is Necessary To Transfer Power. New Developments In Power Electronic Devices Enabled The Power Transfer Through Inductive Coupling Circuits. The Applications Include Consumer Electronics, Electrical Vehicle Charging And Biomedical Devices. Recently Many Research Institutes/Organizations Are Developing WPT (Or) Wireless Charging Technology For Evs. Wireless Charging Provides An Easy To Use, Cost Effective, Safe, And Reliable Way For Charging Evs. WPT Technologies Employ Time-Varying Electric, Magnetic Or Electromagnetic Fields For Power Transfer. The Classification Of Wireless Power Transfer Techniques Are Presented In Fig.1. Mainly Two Technologies Are Employed For Wireless Power Transfer Namely Near Field Or Non-Radiative, And Far Field Or Radiative Method. Near Field Techniques Uses Power Transfer Between Two Inductive Coils By Magnetic Coupling And Capacitive Coupling Between Metal Electrodes By Electric Fields. In Capacitive Coupling Method, To Transfer High Amount Of Power Very Large Electric Fields Are Required. Hence In Most Of The Applications Inductive Coupling Is Adapted. This Method Is Employed For Short Distance Power Transfer Applications Like Mobile Phones, Electric Toothbrushes, Cardiac Pacemakers, RFID Tags, And Electric Vehicles. Far-Field Techniques Employ Electromagnetic Radiation Such As Microwaves Or Laser Beams For Power Transfer. Long Distance Power Transfer Is Possible By These Techniques And Applications Are Solar Power Satellites, And Wireless Powered Drone Aircraft.

The Presence Of The Air Gap In WPT System Creates A Number Of Extraordinary Design Constraints. Because Of Larger Air Gap In The Magnetic Circuit, Low Mutual Inductance And High Leakage Inductances Are Resulted. The Leakage Flux Formed The Eddy Currents In The Core And Creates Power Loss And Magnetic Interference. High Switching Speeds Of Power Electronic Devices Creates Power Loss, High Leakage Inductance And Winding Capacitance[5].

2. TECHNIQUES FOR EV BATTERY CHARGING

In The Recent Past, Inductive Coupled Power Transfer (ICPT), Magnetic Resonance Coupled Power Transfer (MRCPT) And Microwave Power Transfer (MPT) Are The

Technologies Developed For Battery Charging In Evs. The Classification Of Various Wireless Techniques Is Illustrated In Figure 1. Even Though MPT Can Transfer Power For Longer Distances, It Has Some Limitations Such As Higher Cost And Size Of Receiver Antenna, Unsafe To The Living Beings, Applicable For Low Power Level Transmission. IPT Require Closely Placed Primary And Secondary Coils Of An Air Cored Transformer. This Method Has Been Implemented Successfully For Battery Charging In Evs With Small Distance Between Primary And Secondary. If The Distance Is Increased The Efficiency Starts Decreasing Because Of Leakage Reactance. To Overcome This Limitation Of IPT, ICPT Method Was Adapted[5].

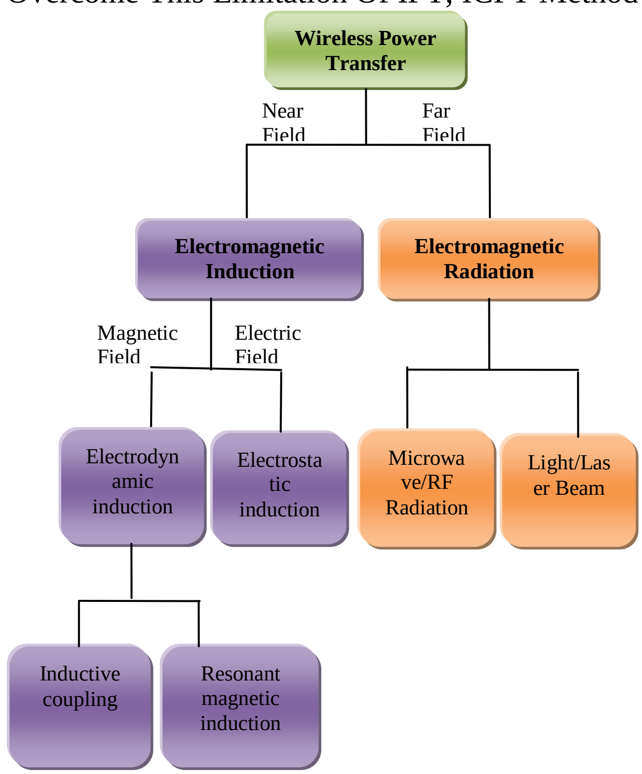

Fig.1 : Classification Of Techniques For Wireless Power Transfer

Wireless Charging Technologies Can Be Broadly Classified Into Non-Radiative Coupling-Based Charging And Radiative RF-Based Charging. Under Non-Radiative Coupling, Three Methods Namely Inductive Coupling[6] , Magnetic Resonance Coupling[7] And Capacitive Coupling[8] Can Be Listed. Radiative RF-Based Charging Can Be Classified Into Directive RF Power Beamforming And Non-Directive RF Power Transfer[9]. In Capacitive Coupling, The Power Transferring Capacity Depends On The Available Area Of The Capacitors. By Using This Method, It Is Difficult To Achieve Required Power Density Even For Typical Size Portable Electronic Devices[10]. The Drawback Of Directive RF Power Beamforming Is That The Transmitter Needs To Locate The Correct Position Of Receiver. Because Of The Drawbacks Of The Above Mentioned Two Techniques, The Other Three Techniques, Namely Magnetic Inductive Coupling, Magnetic Resonance Coupling, And Non-Directive RF Radiation Are Normally Employed For Wireless Charging. The Techniques, Magnetic Inductive Coupling And Magnetic Resonance Coupling Employ Near Field For Its Operation. In These Techniques, The Generated Electromagnetic Field Governs The Proximity Region Which Is Close To The

Transmitter. The Amount Of Power Transmitted Is Inversely Proportional To The Cube Of Charging Distance[11].

On The Other Hand, The Microwave Radiation Uses Far Field Technique To Transfer Power To The Receiver Which Is Positioned At A Longer Distance. In This Technique The Power Transmitted Is Inversely Proportional To The Square Of The Charging Distance[11].
Also In Far-Field Technique, Operation Of Transmitter Is Not Affected By Absorption Of Radiation. But Absorption Of Radiation In The Near-Field Techniques Affects The Load On The Transmitter[12]. Because In The Far-Field Method, A Transmitter And A Receiver Are Not Coupled, But In The Nearfield Techniques, A Transmitting Coil And A Receiving Coil Are Coupled[13].

1) Inductive Coupling:

Magnetic Field Coupling Between Two Coils Is Used For Energy Transfer In The Wireless Charging Systems. Figure 2 Shows The Typical Wireless Inductive Coupled Charging Systems. Transfer Of Inductive Power Occurs When An Energy Transmitter's Primary Coil Produces Uniformly Specific Magnetic Fields Across The Energy Receiver's Secondary Coil. The Coupling Magnetic Force Then Causes Voltage / Current In The Energy Receiver's Secondary Coil. A Wireless Unit Or Storage System Could Be Charged With This Voltage. The Inductive Coupling Operating Frequency Is Usually Within The Khz Range. The Receiver Coil Should Be Tuned At The Frequency Of Operation To Increase The Efficiency Of Charging[14].
The Coils Are Designed With Quality Factors Less Than 10, As The Power Transferred Will Reduce With Increase Of Quality Factor[15, 16]. To Have Larger Coupling Distances, Larger Quality Factor Is The Necessity Feature. To Achieve This Some Kind Of Compensation Is Adapted. Radio Frequency Identification (RFID) Method Is Also An Inductive Coupling Method But Extends The Distance Of Receiving With Decreased Efficiency Of 2-3%. But For The Lesser Transmission Distances, The Amount Of Power Transfer May Be Higher I.E., In Kilowatt Range.

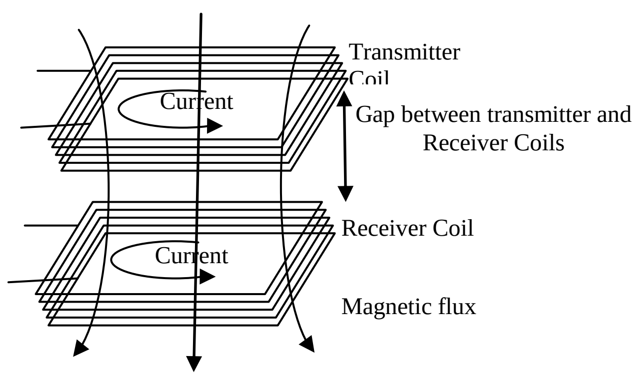

Fig.2 — Inductive Coupling Power Transfer

Inductive Coupled Power Transfer Has Many Advantages Such As Simplicity In Realization Of The System, Guaranteed Safety Operation And Higher Efficiency With Small Distance Between The Coils. This Technology Is Suitable For Electric Vehicles (Both Stationary Charging And On The Go Charging) And Mobile Phones. Magmimo, The Wireless Charging System For Mobile Phones Invented By The MIT Scientists Recently, Can Transfer Power Up To 30 Cm Range[17].

2) *Magnetic Resonance Coupling:*

The Arrangement For Magnetic Resonance Coupling Is Shown In Figure 3 Whose Principle Is Based On Momentary Wave Coupling. The Energy Transfer Takes Place Between Two Coils Operating At Resonant Frequency. Hence, Strong Coupling And Higher Efficiency Is Achieved In This System When Compared Non-Resonant Inductive Coupling. Resonant Operation Of The System Has Some Advantages Like Invulnerable To Adjacent Atmosphere And Efficient Operation Even With Misalignment Of Coils[18].

The Strongly Coupled Resonant Coils Achieve Higher Efficiency And High Energy Transfer With Low Leakage Reactance. The Efficiency Up To 92% Is Achieved With The Gap Of 0.3 Cm[18]. The Advantages Of Resonant Coupled Coils Are It Is Not Affected By Surrounding Fields And Deviation Of Two Coils Is Not Affecting Its Energy Transfer. Magnetically Coupled Transfer System Has The Ability Of Transferring Power Over Larger Gaps Than That Of Inductive Coupled System And Efficient Than RF Radiation Method[19, 20-22]. Moreover, The Energy Can Be Transferred To Multiple Receivers From One Transmitting Coil. Because Of This Property, Parallel Energy Transfer For Many Devices Is Possible[20, 23-26]. But In Order To Reduce The Interference Between Mutual Coupled Coils Should Be Tuned Properly[27].

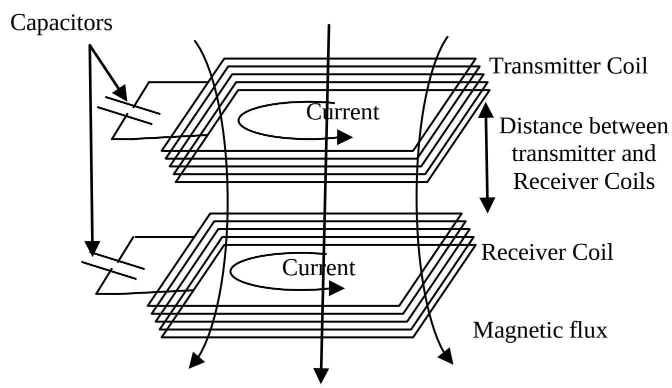

Fig.3 — Magnetic Resonance Coupling Power Transfer

Table 1 — Comparison Of Different Wireless Charging Techniques[33]

Wireless Charging Technique	Advantage	Disadvantage	Effective Charging Distance
Inductive Coupling	Safety For Living Beings, Easy Implementation	Small Power Transfer Distance, Needs Accurate Alignment Between Transmitter And Receiver, Heating Effect, Inappropriate For Mobile Applications	Few Millimeters To A Few Centimeters
Magnetic Resonance Coupling	Loose Alignment Between Transmitter And Receiver, Multiple Devices With Different Power Ratings Can	Limited Charging Distance, Inappropriate For Mobile Applications, Implementation Is	From A Few Centimeters To A Few Meters

	Be Powered Simultaneously, High Power Transfer Efficiency	Difficult	
RF Radiation	Longer Charging Distance, Right Choice For Mobile Applications	Unsecure When Exposed To High Density RF Radiation, Low Power Transfer Efficiency, Line Of-Sight Charging	Tens Of Meters To Many Kilometers

The Quality Factors Of Magnetic Coupled Resonant System Are Of Generally Higher Value Because Their Operating Frequency Is In The Mhz Range. This Property Of Higher Quality Factor Helps To Maintain The Charging Efficiency More Or Less Same For The Increase In Charging Distance.

3) Radiation:
In This Technique Radio Frequency Waves/ Microwaves Are Used As Energy Carriers[28]. These Waves Disseminate In The Environment With The Speed Of Light And In Straight Lines Within A Limited Space. The RF Power Transmitter Consists Of Rectifier Stage And Magnetron Which Produces The RF Radiation. The Frequency Of RF Waves Is In The Range Of 20 Khz To 300 Ghz Which Includes The Microwaves Also[29]. The RF Waves Passing Through The Environment Are Reaching The Receiver Antenna. The Received Signals Are Converted Into Electrical Signals By RF-DC Conversion Process.

The Efficiency Of The Receiver Varies With Many Parameters Such As (I) Power Captured By Antenna, (Ii) Impedance Matching Between Antenna And Voltage Multiplier, (Iii) Efficiency Of Voltage Multiplier[30].

Radio Frequency Waves Or Microwaves Transmitted By The Concept Called Beamforming In Some Directions. The Transmission Efficiency Can Be Improved By Point-To-Point Transmission Called Energy Beamforming. Radio Frequency Waves Are Transmitted Sharply By Antenna Arrays, Which Are Used For Broadcasting[31]. Microwaves Can Be Used To Transmit

Both Power And Information Simultaneously. Modulation Techniques Are Used To Transmit Information Transfer, Whereas Vibration And Radiation Are Used To Transmit Energy[32]. Comparison Of The Above Mentioned Technologies For Wireless Power Transfer Is Presented In Table 1[33].

3. INDUCTIVE COUPLED POWER TRANSFER:

Transformer Is The Simplest Form Of Wireless Power Transfer Between Primary And Secondary Coils By *RF* Mutual Inductance Principle. In A Transformer The Distance Between Coils Are Of Few Centimeters. But To Transfer Power For Longer Distances IPT Is Not Suitable. Power Can Be Transferred Between Two Coils Separated By A Distance Of A Few Meters Efficiently By Using The Resonance Concept. To Achieve The Resonance Condition Capacitors Are Used In Both The Coils As Shown In Figure 4. The Parameters L_T, L_R, C_T, C_R Are

The Inductance And Capacitances On Transmitter And Receiver Side Respectively. The Coupling Coefficient (K) And Mutual Inductance (M) Of The Coupled Circuit Are Related By

$$k = \frac{M}{\sqrt{L_T L_R}} \quad (1)$$

By Designing And Selecting The Inductance And Capacitance For A Particular Resonant Frequency, Maximum Power Can Be Transferred With Lower Coupling Coefficient. Also The Maximum Efficiency Is Achieved When The Two Coils Are At A Certain Distance Which Depends On The Resonant Frequency And Diameter Of The Coil[34].

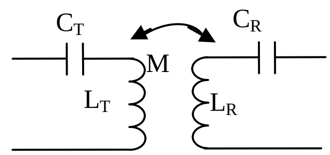

Fig.4 — Inductively Coupled Circuit

4. OPERATING PRINCIPLE FOR ICPT BASED EV CHARGING SYSTEM

An ICPT System Is Loosely Coupled $(k \leq 0.5)$ Systems To Achieve Wireless Power Transfer Which Utilize Advanced Power Conversion, Magnetic Coupling And Control Techniques As Shown In Figure 5. The Transmitter Coil Induces An Emf In The Receiver Coil Because Of Magnetic Coupling Which Is The Voltage Source For The Receiving Side. The Induced Voltage On The Receiver Side Is Unsuitable To Drive The Load Directly As The Coils Are Loosely Coupled. Hence, To Supply Power For The Load Requirements, A Power Conditioner With Proper Circuit Tuning On Both Sides Is Required. To Transfer Maximum Power Between Transmitter And Receiver Coils, Perfect Resonance To Be Achieved. The Power Transfer Efficiency Of ICPT Can Be Analyzed By The Equivalent Circuit Of The System. Series Compensated Circuits On Both Sides Is Chosen For Analysis Because Of Its Simplicity And Minimum Number Of Parameters Involved In The Optimization Of Efficiency. The Equivalent Circuit Of Series-Series Compensated Circuits Is Sown In Figure 6[34, 35].

From The Equivalent Circuit, The Total Impedance Can Be Written As[34, 35],

$$Z_s = \left(R_T + j\left(L_T\omega - \frac{1}{C_T\omega}\right)\right) + \left(\frac{\omega^2 M^2}{R_R + j\left(L_R\omega - \frac{1}{C_R\omega}\right) + R_L}\right) \quad (2)$$

The Current Supplied By The Source Is Given By

$$I_s = \frac{V_s}{Z_s} = \frac{V_s}{\left(R_T + j\left(L_T\omega - \frac{1}{C_T\omega}\right)\right) + \left(\frac{\omega^2 M^2}{R_R + j\left(L_R\omega - \frac{1}{C_R\omega}\right) + R_L}\right)} \quad (3)$$

If The Circuit Is Assumed To Operate At A Resonant Frequency f_r Only Resistance Present In The Circuit And Hence Source Current Is Given By

$$I_s = \frac{V_s}{R_T + \left(\frac{\omega_r^2 M^2}{R_R + R_L}\right)} \quad (4)$$

The Source Power Can Be Calculated As

$$P_s = \frac{{V_s}^2}{R_T + \left(\frac{\omega_r^2 M^2}{R_R + R_L}\right)} = \frac{{V_s}^2 (R_R + R_L)}{R_T R_R + R_T R_L + \omega_r^2 M^2} \quad (5)$$

The Output Power Is Obtained By

$$P_L = \frac{V_S{}^2}{R_T+\left(\frac{\omega_T^2M^2}{R_R+R_L}\right)} = \frac{V_S{}^2\omega_T^2M^2R_L}{\left(R_TR_R+R_TR_L+\omega_T^2M^2\right)^2} \quad (6)$$

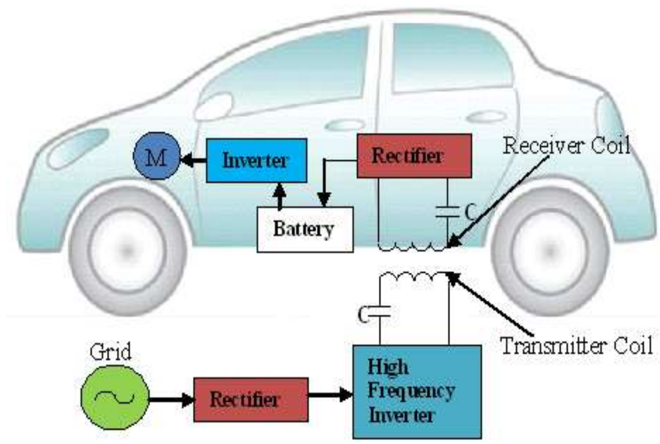

Fig.5 — Resonant Inductive Coupled Charging System For Electric Vehicles

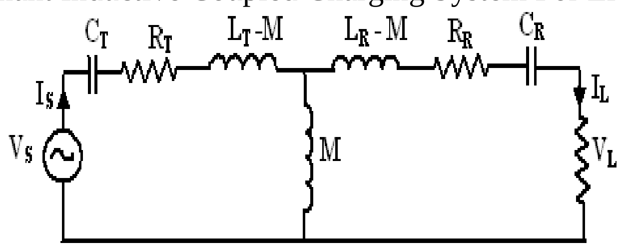

Fig.6 — Equivalent Circuit Of Series-Series Tuned Coupled Circuit

So, The Efficiency Of The ICPT System Is Given By

$$\eta = \frac{P_L}{P_s} = \frac{\omega_T^2M^2R_L}{(R_R+R_L)\left(R_TR_R+R_TR_L+\omega_T^2M^2\right)} \quad (7)$$

By Simplifying The Efficiency Can Be Written As[36]

$$\eta = \frac{R_L}{R_L+R_R+R_T\left(\frac{(R_L+R_R)}{\omega_T M}\right)^2} \quad (8)$$

The Dependency Of Efficiency Of ICPT System On The Coupling Coefficient Can Be Obtained From Eqn. (7) By Modification As Follows,

$$\eta = \frac{k^2(2\pi f_r)^2L_TL_RR_L}{(R_R+R_L)(R_TR_R+R_TR_L+k^2(2\pi f_r)^2L_TL_R)} \quad (9)$$

5. EFFICIENCY OF WPT SYSTEM

The Efficiency Of A WPT System Varies With Many Parameters, But The Distance Between Primary And Secondary Coil And Alignment Of Primary And Secondary Coil Are Greatly Affecting It. If The Distance Between The Primary And Secondary Coil Changes, The Efficiency Vary Because Of The Flux Linkages Between Them Changes. Inverter Current Also

Changes As The Load Seen From The Primary Coil Vary With Respect To Distance. If The Distance Increases, The Power Transfer And Efficiency Of WPT Decrease Due To Weaker Coupling Between Coils. Figure 7 Illustrates The Variation Of Efficiency With Respect To The Vertical Distance Between The Coupling Coils. Actually Magnetic Field Is Diminishing Proportional To $1/D^3$ Approximately[34].

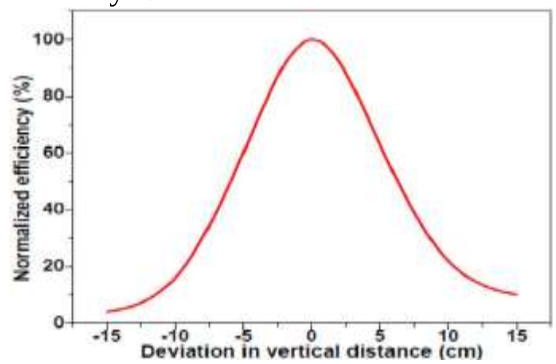

Fig.7 — Variation Of Efficiency With Vertical Distance Between Coils

Misalignment Or Horizontal Distance Between Primary And Secondary Coils Has Similar Effect On System Efficiency. As The Distance Between The Centers Of Coils Is Measured On Diagonal Plane, Decrease In Efficiency Is Higher Per Centimeter Of Misalignment. Hence An Adaptive Control System Which Changes The Position Of Coils And Aligns A Position To Match The Input-Output Impedances And Achieve Maximum Power Transfer Is Required. The Impedance Matching Is Achieved By Tuning The Frequency Or For A Particular Operating Frequency, Adaptive Impedance Matching Networks Could Be Used. Figure 8 Illustrates The Dependency Of Efficiency On Frequency For Different Values Of Coupling Coefficient Or Mutual Inductance[34].

6. APPLICATIONS OF WPT:

Wireless Charging Can Be Implemented By Using Either Near-Field Or Far-Field Method. Wireless Charging Is Employed In Diverse And Promising Applications In Both Industries And Transport Systems. WPT Is Increasingly Used In Medical Equipments, Robot Manipulators, Consumer Electronic Devices,

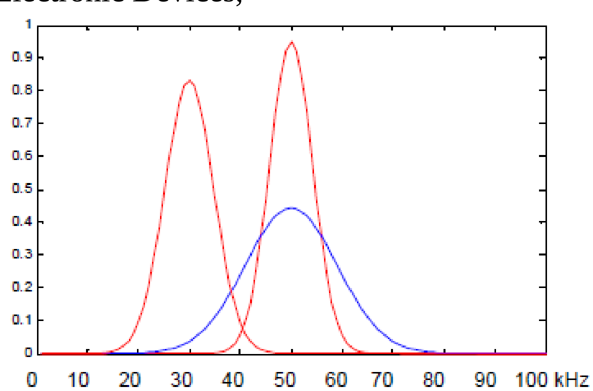

Fig.8 — Variation Of Efficiency With Frequency

Industrial Electronic Devices And Transport Systems. It Is Suitable For Electric Vehicles As It Provides Isolation Between Charging And Receiving System And Customizable Under Harsh Environments. This Method Can Transfer Power Upto 100s Of Kilowatts With Efficiency Of About 80% And More[6].

7. WPT STATUS WORLDWIDE

Recently Many Institutes/Research Organizations Developed Wireless Charging System With Different Capacities And Techniques. The Important Developments Of WPT System In The Recent Past Are Listed In Table. 2. There Are Developments In All The Range From Small (3.3 Kw) To Larger (1000 Kw) Capacities But All Of Them Having Efficiency Around 90% For The Coil-Coil Distance Range Of 15 Cm.

Witricity Corporation Introduced Highly Resonant WPT Charging System For The Capacity In The Range Of 3.6 To 11 Kw With Overall System Efficiency Of 90%[37]. Oak Ridge National Laboratory (ORNL) And Toyota Motor Engineering And Manufacturing North America (TEMA) Closely Worked Together In Developing Wirelesss Charging Systems For Electric Vehicles. The Project Involves The Vehicle Integration Plans, Compatibility, And The Interoperability Of The Wireless Charging Technology For TOYOTO Vehicles. The Vehicles Namely Are Toyota Prius Plug-In Hybrid Electric Vehicle, A Scion Iq Electric Vehicle, And Two Toyota RAV4 Electric Vehicles. The Investigation Comprised Of Integrating Hardware For Charging System, Respective Control And Communication System, And Automating Charging Process. ORNL Developed Two Wireless Charging Systems For Scion IQ EV, And Toyoto RAV4 EV With Capacity Of 6.6 Kw And 20 Kw Respectively[38, 39].

Korea Advanced Institute Of Science And Technology (KAIST) Introduced Online Electric Vehicle (OLEV) Concept Using The Technique Namely Shaped Magnetic Field In Resonance (SMFIR) For Charging The Batteries In The Vehicle While It Is Moving. The Charging Pads Are Fixed In The Middle Of The Road Track About 10-15 % Of Road Width. Two Buses Were Operating On A 24 Km Distance Road Line In The City Of Gumi, South Korea In The Year 2013. Reduction Of Battery Size Upto 1/5 Times Is Possible Because Of Powering The Batteries On The Go[38, 40].

During 2013, Another Investigation Was Carried Out By KAIST And The Korea Railroad Research Institute (KRRI) Combinedly For Wireless Power Transfer For Electric Trams And Trains. This Research Employed Same SMFIR Technique For On The Go Charging With 180 Kw Capacity Of Power Transfer. There Are Many

Table 2 — WPT Project Status

Name Of The Organization/Project	Capacity (Kw)	Efficiency (%)	Air Gap (Cm)	Frequency Of Operation (Khz)	Year	Technique Used/Project Name
Oak Ridge National Laboratory[38, 39]	20	90	160	22	2016	Toyota RAV4 EV
	6.6	85	165	22	2016	Scion IQ EV

Witricity[37]	3.6-11	90	15-200	NA	2011	Highly Resonant (HR) WPT
Korea Advanced Institute Of Science And Technology (KAIST)[38, 40]	100	85	17	20	2013	SMFIR/OLEV (Shaped Magnetic Field In Resonance/Online Electric Vehicle)
Korea Railroad Research Institute (KRRI)[38, 41]	1000	82.7	5	60	2014	SMFIR/OLEV
Utah State University & Wireless Advanced Vehicle Electrification Electrification (WAVE)[38, 42]	50-500	90	15-25	20	2014 - 2019	Wireless Advanced Vehicle Electrification (WAVE)
Bombardier[38, 41]	200	90	30-40 (Automatic Positioning System Integrated)	NA	2016	PRIMOV IPT
Qualcomm Halo[38, 43]	3.7, 11, 18 And 22	90	15-25	20-140	2012	WEVC
Qualcomm Halo[38, 43]	20		15-20	85	2016	DEVC
EVATRAN[38, 44]	3.3, 6.6, 7.2	90	10	19.5	2014	Plugless
Eaton HEVO[38, 45]	200-1000	85-92%	15	85	2017	Hypercharger
Momentum Dynamics[38,46]	30-450	>90	Upto 30	85	2016	Momentum Wireless Power

Improvements Have Been Reported Such As Reduced Size And Weight Of Onboard Charging System, Increased Power Transmission Density, And Reduction In Production Cost[38, 41].

Electric Vehicle & Roadway (EVR) Research Facility Under Sustainable Electrified Transportation Centre (SELECT) At Utah State University, USA, Has State Of The Art 4800 Ft^2, $_{1/4}$ Miles Length Wireless Charging Track, 750 Kw Utility Power And Allied Infrastructure. Wireless Advanced Vehicle Electrification (WAVE) Inc. Spin-Out By Utah State University Is A Solution Provider For Wireless Charging Systems For Electric Vehicles. Antelope Valley Transit Authority (AVTA) Deploys Multiple WAVE 250 Kw

Chargers In 2018 For Charging BYD K11 And K9 Buses Which Will Replace The Diesel Counterparts Completely. WAVE's 50 Kw Chargers Are Deployed At Long Beach, CA For Powering BYD Buses In 2018. For Powering Drayage Trucks At Port Of Los Angeles, WAVE In Partnership With Cummins Inc., Schneider Electric, Utah State University And Total Transportation Services Inc. (TTSI) Develop And Demonstrate A First-Of-Its-Kind 500 Kw "XMEG" High-Power Extreme Fast Charging Wireless Inductive Charger In 2019[38, 42].

Bombardier's PRIMOVE Wireless Power Transfer Technology Was Adapted To Operate A Scania Bus In The City Södertälje, Sweden During 2016. A Charging Station Located At The Södertälje Terminus With 200 Kw Capacity Takes 6-7 Minutes To Transfer The Energy Required To Travel The Route Distance Of 10 Km[38, 41].

Qualcomm Halo Wireless Electric Vehicle Charging (WEVC) Technology Was Exhibited At Consumer Electronics Show At Las Vegas, Nevada, USA. Variety Of System With 3 Kw, 7 Kw, 11 Kw, 18 Kw And 22 Kw Power Capacity And Frequency Range Of 20-140 Khz Were Exhibited. Qualcomm Technology Inc. (QTI)'S Dynamic Electric Charging System (DEVC) System Installed At Satory, Versailles, Near Paris Has 100-Meter FABRIC Test Track, Which Has Been Built By Vedecom. The 100-Meter Roadway Consists Of 4 Numbers Of 25 Meter Stubs. Each Stub Gets Power From Its Own Power Supply. Each Stub Can Provide Power To 14 Numbers Of Base Array Network (BAN) Blocks Which Are Coupled Magnetically Into The Backbone Cable[38, 43].

In 2009, Evatran Started Development Of Plugless Power, An Inductive Charging System For Charging Electric Vehicles. Evatran Plugless Is Developed For BMW I3, Tesla Model X, Chevy Bolt, Ford Evs With 7.2 Kw Capacity. One More 6.6 Kw IPT Device Developed Is For Nissan Leaf[38, 44]. Eaton Corporation Declared Fast Wireless Chargers Namely HEVO Hypercharger, Which Were Available Commercially In The Range Of 200 Kw To 1000 Kw[38, 45] For Buses And Trucks In 2013. These Charging Systems Are Installed At Locations Such As Tallahassee, Florida, Worcester, Massachusetts And Stockton, California For Powering The Proterras Ecoride Bus. Momentum Dynamics Have Developed High Power And Efficient Wireless Charging Systems For All Kind Of Vehicles In The Range 30 Kw To 450 Kw. The Systems Are Capable Of Transferring Power Under Rain And Snow With A Distance Of 12 Inch[38, 46].

8. CHALLENGES OF WPT SYSTEMS

A Few Foremost Challenges Related With The Practical Implementations Of WPT System Are:

- *Supplying The Load Demand:* Due To Space Constraint On The Receiver Of WPT, It Is Difficult To Transfer The Required Power To A Load.
- *Switching Speed:* High Frequency Of Operation Helps To Reduce Overall System Size, But Finding Suitable Devices For High Frequency Operation Is Cumbersome. The Commercial

Product Suitable For WPT Operation With Switching Frequency Of 80 Mhz And Ratings 3kv/2ka Is IGBT.

• *Obtaining High Efficiency:* The Iron Losses And Copper Losses Occur In Various Parts Of The System Reduces The System Efficiency.

• *Allowable Temperature Rise:* The WPT System May Be Operated Under Different Hot And Cold Climates. The System Should Operate Safely Within The Maximum Limit Of Temperature Rise.

• *System Size/Weight:* The Power Transfer Process Requires Components Such As Core, Coil, Capacitor Etc. Which Are Bulky And Heavy In Nature. Such Components Increase The Size And Weight Of The WPT System.

• *System Stability And Control:* It Is Necessary To Design A Stable System Which Can Operate With Whole Range Of Load And Variable Frequency. Improper Design Of WPT Systems Lead To Instability Under Variable Frequency Operation.

• *Cost:* Generally WPT Systems Involve More Power Electronics And Magnetic Components. So That They Are Costlier Compared To Wired Charging Systems. Minimizing The Cost With Improved Design Constraints Is A Cumbersome Task.

• *Electromagnetic Compatibility:* WPT Systems Should Undergo The Electromagnetic Compatibility Tests And Other Safety Standards, Which Is Also One More Challenging Engineering Design Task.

Optimizing For All The Constraints Is Become Difficult For A Practical WPT System. So Trade-Offs Between The Parameters Is Adapted According To Situation And Application[5].

When Compared To Wired Battery Charging, WPT Need The High Frequency Power Electronics And Associated Infrastructure, Which Increases The Overall Cost Of The System. This Higher Cost Can Be Acceptable Because Of The Advantages Of WPT Like Reduced Battery Size, Convenience, Reduced Levelised Life Time Cost Of The Vehicle. Another Challenge Is The Lack Of Charging Infrastructure. Government Has To Take Initiatives To Install The Charging Stations By Providing Subsidy, Required Clearances, And Incentives Through Private Or Government Agencies. Indian Government Made Announcement To Install The Charging Stations In Four Metropolitan Cities (Delhi, Mumbai, Kolkata, And Chennai) As The First Initiative. Existing Petrol And Gas Bunks Will Be Given Preference To Install Such Charging Stations[5].

Real-Time Communication Between Vehicle And Charging System Plays A Very Important Role In Efficient And Timely Charging In WPT. Real-Time Control Systems Are Employed To Monitor The Parameters In The Charging System. Research & Development Of Minimum Latency And Longer Range Communication Architectures For WPT Have To Be Focused In The Near Future.

The Effect Of Magnetic Field Of WPT Over The Living Beings Is Another Issue To Be Resolved. International Commission On Non-Ionizing Radiation Protection (ICNIRP) Provides Scientific Advice And Guidance On The Health And Environmental Effects Of Non-Ionizing Radiation (NIR) To Protect People And The Environment From Detrimental NIR Exposure. Human Tissues Are Get Affected When It Is Exposed To Electric And Magnetic Fields. ICNIRP Released The Limits For Electric Field And Magnetic Field For Human Tissues. Reference Levels Provided By ICNIRP For Whole Body Exposure To Time-Varying Far-Field Electric, Magnetic And Electromagnetic Fields, With Frequency In The Range 100 Khz To 300 Ghz Are Listed In Table 3. *F* Is The Frequency In Mhz[36].

Table 3. Reference Levels For Whole Body Exposure To Time-Varying Far-Field Electric, Magnetic And Electromagnetic Fields

Exposure Scenario	Frequency Range	E-Field Strength ($V\ M^{-1}$)	H-Field Strength ($A\ M^{-1}$)	Incident Plane Wave Power Density (S_{inc}) ($W\ M^{-2}$)
General Public	0.1-20 Mhz	*560/F*	*2.2/F*	----
	>20-30 Mhz	*28*	*2.2/F*	----
	>30-400 Mhz	*28*	*0.073*	*2*
	>400-2,000 Mhz	$1.375f^{0.5}$	$1.375f^{0.5}$	*F/200*
	>2-300 Ghz	----	----	*10*

Aluminum Shielding Provided At The Back Of The Charging Pad Can Efficiently Block The EMF Exposure To The Passengers In The Vehicle[47]. Anyway, Further Research On The Exposure Of Living Beings To Magnetic Field Is Required To Ensure Health And Safety Of People. For Dynamic Charging Systems Installed In Open Space Roads, Research To Be Done With Various Conditions Such As Unintentional Leakage, Living Object Detection, Foreign Object Detection, Varying Speed Of Vehicle, And People With Implanted Medical Device Etc[47].

9. CONCLUSION

This Paper Presents An Overview And Status Of Wireless Charging Of Electric Vehicles. In The Present Time Because Of Environment Concerns, Depletion Of Fossil Fuels Makes Electrifying The Transport Important. Electric Vehicles Need Charging Of Batteries By Any Means. Wired And Wireless Charging Of Electric Vehicles Is Possible. But Wireless Charging Method Offer Advantages Compared To Wired Charging. Research On Both Static And Dynamic Wireless Charging Is Improving Year By Year. By Installing On The Go (Dynamic) Charging Systems In The Roads, Capacity Of Batteries On The Vehicle Can Be Of Small Capacity. Wireless Charging Of Evs Comes Into Existence With Advanced Technology Development. However, The Technology Is Still Immature And More Research Issues Are To Be Solved. Development Of *On-The-Go-Charging* Systems Is The Future Scope Of Wireless Charging. Further Research On Power Electronic System Design And Control, Different Topology Of Inverters, Living Being Safety Etc., Are Still Need To Improve.

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