DEVELOPMENT OF CONTROL SYSTEMS WITH PERFORMANCE ASSESSMENT OF HYBRID TRACKED VEHICLES

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by

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Certificate

This is to certify that the thesis entitled **"Development of Control Systems with Performance Assessment of Hybrid Tracked Vehicles"**, being submitted by **Joshua Raj Kumar Aska** to the **Indian Institute of Technology Delhi** for the award of the degree of Doctor of Philosophy is a record of the bonafide research carried out by him which has been prepared under my supervision in conformity with the rules and regulations of the Indian Institute of Technology Delhi. He has fulfilled all requirements for the submission of his thesis, which has attained the standard required for a Ph.D. degree of the Institute. The research reports and results presented in the thesis have not been submitted for any degree in any other university or institute.

Place: New Delhi

Date:

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Place: New Delhi

Date: (Joshua Raj Kumar Aska)

Abstract

This study focuses on the development of control systems of a hybrid propulsion system (IC Engine and Electric Motor) for a heavy tracked vehicle and the assessment of performance such as power, torque, energy efficiency, emissions and costs. Advances in automobile technology have led to the widespread adoption of hybrid drivetrains in passenger vehicles as a promising alternative to traditional Internal Combustion Engines (ICE) presenting significant advances toward a more sustainable and energy-efficient future for passenger transportation. However, hybrid technology in tracked vehicles is still in nascent stages, with considerable potential for development and practical benefits. Tracked vehicles' unique design feature a drivetrain with a continuous track system that distributes weight evenly offering superior traction and stability on rough, uneven terrain, which is vital in military, farming, construction and mining operations.

In this study, a tracked military vehicle, with a diesel Internal Combustion Engine (ICE) of 221 kW, was virtually substituted by a hybrid propulsion system with 68.5 kW IC Engine and 112 kW Electric Motor (EM) in parallel configuration (62% Degree of Hybridisation) in MATLAB Simulink. The parameters of IC Engine, Motor, target vehicle, Modified Indian Drive Cycle (MIDC), and battery characteristics were provided as inputs to the MATLAB Simulink for operation of the hybrid system. The control systems incorporate tailor-made algorithms while facilitating peculiar tracked vehicle functions like braking, clutching, turning, and gear shifting. The novelty of this research lies in the development, integration, and validation of an optimised hybrid control strategy for heavy tracked vehicles. A supporting contribution is the novel assessment methodology, which systematically quantifies performance, energy efficiency, fuel consumption, energy recovery from regenerative braking, range enhancement, CO_2 emission, carbon penalty from cradle-to-gate and running costs.

The developed hybrid system with 180.5 kW could provide the performance (power and torque with respect to speed) equivalent of 221 kW IC Engine under MIDC conditions and satisfactorily maintained the velocity profile of the MIDC within a mean variance of 1.28 km/h with braking, gear shifting, clutching, and turning functions as required. The developed hybrid system could achieve regenerative efficiency of 14.24% and a 14.44% theoretical increase in range compared to the IC engine. Range analysis suggests IC engines and hybrids suit heavier highway vehicles, while grid-based EVs are better for lighter, urban, short-distance driving. The carbon footprint of the IC engine was the highest, at 33% more than the electric system and 22% more than the hybrid system. Cumulative running cost (including carbon price) of the hybrid and electric power sources was lower than the IC engine, with cost savings of 72% for the hybrid source and 86% for the electric, electric power source being the lowest.

Notable conclusions that emerged from this study suggest that a hybrid propulsion system with 62% Degree of Hybridisation (62% Electric, 38% IC Engine) is suitable for heavy tracked vehicles operating on Modified Indian Drive Cycle (MIDC), based on power density, velocity, driving range, energy consumption, regenerative efficiency, decrease in carbon footprint and reduced operating costs. The development of hybrid propulsion system with control strategy including the performance and cost analysis performed in this study advances the development of scalable hybrid propulsion systems as credible alternatives to conventional IC engines for heavy tracked vehicles.

सार

यह अध्ययन एक भारी ट्रैक वाले वाहन के लिए हाइब्रिड प्रणोदन प्रणाली (आईसी इंजन और इलेक्ट्रिक मोटर) की नियंत्रण प्रणालियों के विकास और शक्ति, टॉर्क, ऊर्जा दक्षता, उत्सर्जन और लागत जैसे प्रदर्शन के आकलन पर केंद्रित है। ऑटोमोबाइल प्रौद्योगिकी में प्रगति ने पारंपरिक आंतरिक दहन इंजन (ICE) के एक आशाजनक विकल्प के रूप में यात्री वाहनों में हाइब्रिड ड्राइवट्रेन को व्यापक रूप से अपनाया है, जो यात्री परिवहन के लिए अधिक टिकाऊ और ऊर्जा-कुशल भविष्य की दिशा में महत्वपूर्ण प्रगति पेश करता है। हालांकि, ट्रैक वाले वाहनों में हाइब्रिड तकनीक अभी भी प्रारंभिक अवस्था में है, जिसमें विकास और व्यावहारिक लाभों की काफी संभावनाएं हैं। ट्रैक वाले वाहनों के अनूठे डिजाइन में एक निरंतर ट्रैक प्रणाली के साथ एक ड्राइवट्रेन है जो वजन को समान रूप से वितरित करता है और उबड़-खाबड़, असमान इलाके पर बेहतर कर्षण और स्थिरता प्रदान करता है, जो सैन्य, खेती, निर्माण और खनन कार्यों में महत्वपूर्ण है।

इस अध्ययन में, 221 kW के मानक डीजल आंतरिक दहन इंजन (ICE) के साथ एक सामान्य रूप से उपयोग किए जाने वाले ट्रैक किए गए सैन्य वाहन को चुना गया और वस्तुतः एक हाइब्रिड प्रणोदन प्रणाली (62% हाइब्रिडाइजेशन की डिग्री) द्वारा प्रतिस्थापित किया गया, जिसमें MATLAB सिमुलिंक वातावरण में समानांतर विन्यास में 68.5 kW IC इंजन और 112 kW इलेक्ट्रिक मोटर (EM) थी। इनपुट मापदंडों का उपयोग करके आनुपातिक इंटीग्रल (PI) नियंत्रण के साथ नियंत्रण प्रणाली, जैसे कि IC इंजन, मोटर, वाहन मापदंडों, संशोधित भारतीय ड्राइव साइकिल (MIDC) मापदंडों (टॉर्क, पावर, गति विशेषताओं), और बैटरी के चार्ज की स्थिति, को हाइब्रिड सिस्टम के संचालन के लिए MATLAB सिमुलिंक वातावरण में विकसित किया गया था। एक सहायक योगदान नवीन मूल्यांकन पद्धति है, जो व्यवस्थित रूप से प्रदर्शन, ऊर्जा दक्षता, ईंधन खपत, पुनर्योजी ब्रेकिंग से ऊर्जा प्राप्ति, रेंज वृद्धि, CO_2 उत्सर्जन, क्रैडल-टू-गेट से कार्बन पेनाल्टी और परिचालन लागत का आकलन करती है।

180.5 kW के साथ विकसित हाइब्रिड प्रणाली MIDC परिस्थितियों में 221 kW IC इंजन के बराबर प्रदर्शन (गति के संबंध में शक्ति और टॉर्क) प्रदान कर सकती है और ब्रेकिंग, गियर शिफ्टिंग, क्लचिंग और आवश्यकतानुसार मोड़ने वाले कार्यों के साथ MIDC के वेग प्रोफ़ाइल को 1.28 किमी/घंटा के औसत विचरण के भीतर संतोषजनक रूप से बनाए रखा है। विकसित हाइब्रिड प्रणाली IC इंजन की तुलना में 14.24% की पुनर्योजी दक्षता और सीमा में 14.44% की सैद्धांतिक वृद्धि प्राप्त कर सकती है। सीमा विश्लेषण से पता चलता है कि IC इंजन और हाइब्रिड भारी राजमार्ग वाहनों के लिए उपयुक्त हैं, जबकि ग्रिड-आधारित EV हल्के, शहरी, कम दूरी की ड्राइविंग के लिए बेहतर हैं। IC इंजन का कार्बन फुटप्रिंट सबसे अधिक था, जो इलेक्ट्रिक सिस्टम से 33% गुना और हाइब्रिड सिस्टम से 22% गुना हैं। हाइब्रिड और इलेक्ट्रिक पावर स्रोतों की संचयी परिचालन लागत (कार्बन मूल्य सहित) आईसी इंजन की तुलना में कम थी, हाइब्रिड स्रोत के लिए लागत बचत 72% और इलेक्ट्रिक के लिए 86% थी, इलेक्ट्रिक पावर स्रोत सबसे कम था।

इस अध्ययन से निकले उल्लेखनीय निष्कर्ष बताते हैं कि 62% हाइब्रिडाइजेशन (62% इलेक्ट्रिक, 38% आईसी इंजन) वाला एक हाइब्रिड प्रणोदन प्रणाली, शक्ति घनत्व, वेग, ड्राइविंग रेंज, ऊर्जा खपत, पुनर्योजी दक्षता, कार्बन फुटप्रिंट में कमी और कम परिचालन लागत के आधार पर, मॉडिफाइड इंडियन ड्राइव साइकिल (एमआईडीसी) पर चलने वाले भारी ट्रैक वाले वाहनों के लिए उपयुक्त है। इस अध्ययन में किए गए प्रदर्शन और लागत विश्लेषण सहित नियंत्रण रणनीति के साथ हाइब्रिड प्रणोदन प्रणाली का विकास, भारी ट्रैक वाले वाहनों के लिए पारंपरिक आईसी इंजनों के विश्वसनीय विकल्प के रूप में स्केलेबल हाइब्रिड प्रणोदन प्रणालियों के विकास को आगे बढ़ाता है।

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Nomenclatures

a	Vehicle Acceleration
A	Ampere
A_f	Frontal area of the Vehicle
Ah	Ampere Hour
AFV	Armoured Fighting Vehicle
APC	Armoured Personnel Carrier
BEV	Battery Electric Vehicle
BMS	Battery Management System
BS	Bharat Stage
cc	Cubic Capacilty
CC/ACC	Capital Cost/Annual Capital Cost
C_d	Aerodynamic drag coefficient
CIEV	Compression Egnition Engine Vehicle
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CRF	Capital Recovery Factor
DoD	Depth of Discharge
DoH	Degree of Hybridisation
DPF	Diesel Particulate Filters

ECR	Effective Carbon Rates
ECU	Engine Control Unit
EGR	Exhaust Gas Recirculation
EM	Electric Motor
EMS	Energy Management Strategy
EPA	Environmental Protection Agency
EU	European Union
EV	Electric Vehicle
FOM	Fixed Operating and Maintenance Costs
F_a	Aerodynamic drag
F_{acc}	Acceleration Force
F_g	Gradient Resistance
F_{rr}	Frictional Resistance Force
F_{tr}	Tractive Effort required
g	Gravitational Acceleration
GHG	Green House Gases
gm	Gram
Gm/hp h	Gram per Horse Power Hour (Specific Fuel Consumption)
GPS	Global Positioning System
HEV	Hybrid Electric Vehicle

HP/hp	Horse Power
ICE	Internal Combustion Engine
ICV	Infantry Combat Vehicle
Km/h	Kilometre per Hour
kW	Kilo Watt
kWh	Kilo Watt Hour
L	Litre
LCA	Life Cycle Assessment
MJ	Mega Joule
m	Vehicle mass
MAER	Mobile Agricultural Equipment Regulation
MATLAB Simulink	Simulation and modeling environment
MBT	Main Battle Tank
MIDC	Modified Indian Drive Cycle
MoRTH	Ministry of Road Transport and Highways
NEDC	New European Driving Cycle
N-m	Newton Metre
NO_x	Nitrous Oxides
OECD	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer

P	Proportional
PI	Proportional Integral
PID	Proportional Integral Derivative
PHEV	Plug In Hybrid Vehicle
PID	Proportional–Integral–Derivative Controller
RPM/rpm	Revolutions Per Minute
SCR	Selective Catalytic Reduction
SD/ σ	Standard Deviation
SE	Standard Error
SFC	Specific Fuel Consumption
SoC	State of Charge
t	Time
Δt	Time interval
US	United States of America
UK	United Kingdom
v	Vehicle velocity
V	Voltage
Wh	Watt Hour
WLTC	Worldwide Harmonized Light Vehicle Test Cycle
α	Angle of Inclination

δ	Percentage Increase in Battery Capacity
ξ	Range per unit Kilo Watt Hour
σ	Standard Deviation (SD)
ρ	Density of air
μ_{rr}	Coefficient of Friction