POWER FACTOR CORRECTION IN SWITCHED RELUCTANCE MOTOR DRIVES

ANIKET ANAND

DEPARTMENT OF ELECTRICAL ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY DELHI

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by

ANIKET ANAND

Department of Electrical Engineering

Submitted

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CERTIFICATE

This is to certify that the thesis entitled **"Power Factor Correction in Switched Reluctance Motor Drives,"** being submitted by **Mr. Aniket Anand** for the award of the degree of **Doctor of Philosophy** is a record of a bonafide research work carried out by him in the Department of Electrical Engineering of Indian Institute of Technology Delhi.

Mr. Aniket Anand worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which to my knowledge has reached the requisite standard. The results obtained herein have not been submitted to any other University or Institute for the award of any degree.

Dated: May 13, 2019

(Prof. Bhim Singh)

Department of Electrical Engineering,
Indian Institute of Technology, Delhi

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Aniket Anand

ABSTRACT

With the increased in energy demand, the design and development of energy efficient drive for domestic and industrial appliances, have become essential. The current harmonic regulations limit the harmonics emission by the household equipment so that it does not exceed the compatibility levels. These regulations also define the minimum power factor required for the equipment connected to single phase supply. Therefore, the drives are recommended with front end PFC (Power Factor Correction) converters to increase the power conversion efficiency and to meet the international standards for power quality, such as IEC-61000-3-2. The research in power converters has developed the keen interest of researchers in special machines, which has been developed in late nineteenth century. Brushless DC motor, permanent synchronous motor, synchronous reluctance motor and switched reluctance motor (SRM) are some of the motors, which are seeking the attraction for number of applications.

This work aims at the development of the power factor correction converters for feeding SRM drive as a cost effective solution for low power household applications. The cost and efficiency are two most important aspects, which play a vital role in the design of drives focusing towards households applications such as fans, water pumps, vacuum cleaner, washing machine etc. SRM has salient pole construction such that the stator is provided with concentrated windings, which are excited through mid-point converter, sequentially. The rotor is made up of laminated magnetic materials and free from any sort of winding. SRM has many advantages such as high torque-volume ratio, fast dynamic response, low manufacturing cost and wide speed range.

The selection of suitable PFC converter for particular application depends upon various aspect including rating of SRM motor, voltage and current rating of semiconductor devices, total number of component counts, requirement of two equal output voltages, galvanic isolation, cost and efficiency of the overall system. Out of the available PFC converter configurations, the recommended PFC converters for the proposed SRM drive, are classified into five different categories of non-isolated single output PFC converters, non-isolated dual output PFC converters, isolated single output PFC converters, isolated dual output PFC converters and bridgeless PFC converters. Among them dual output PFC converters are mainly focused as per the system requirement, as two equal output voltages are required to feed the mid-point converter fed SRM drive. In this work, PFC converters are designed to operate in DCM, to obtain inherent power

factor correction at supply mains. As the voltage follower approach is considered, therefore, sensor requirement is reduced to one voltage sensor, which reduces the system cost.

The major aspect of the work, includes simplicity in control as two equal output voltages are generated to feed the mid-point converter fed SRM drive without any voltage balancing loop. The converter configurations proposed for the SRM drive, are features with neutral point N to generate, which has reduced the stress across the semiconductor switches. Moreover, the selected DCM of operation via voltage follower approach requires simple control to obtain inherent power factor correction at input side. In this technique, PFC is obtained due to discontinuous inductor current mode during each switching period. During this period, the circuit behaves as an emulated resistance, and thus inherent wave-shaping is provided to the circuit. The controlled DC link voltage over wide range, delivers excellent speed control, which is well demonstrated in the test results. The performance of proposed PFC converters fed SRM drive is validated on the models developed in MATLAB/Simulink environment. Further, to validate the simulation results, a laboratory prototype of PFC converter fed SRM drive is developed. However, the performance evaluation of proposed SRM dive is carried out during different steady state and dynamic conditions. The voltage and current waveforms of different circuit components including circuit inductor, capacitor and semiconductor switches are analysed. The proposed PFC converters fed SRM drive is also tested under different supply voltage fluctuation conditions, which is well demonstrated through test results. The accepted power quality indices of these PFC converters fed SRM drive are also evaluated at AC mains. The found indices comply with the given power quality standard IEC 61000-3-2.

आब्स्ट्रॅक्ट

वित थे इनक्रीस्ड इन एनर्जी डिमँड, थे डिज़ाइन आंड डेवेलपमेंट ऑफ एनर्जी एफीशियेंट ड्राइव फॉर डोमेस्टिक आंड इंडस्ट्रियल अप्लाइयेन्सस, हॅव बिकम एसेन्षियल. थे करेंट हारमॉनिक रेग्युलेशन्स लिमिट थे हारमॉनिक्स एमिशन बाइ थे हाउशोल्ड एक्विपमेंट सो तट इट डज़ नोट एक्सीड थे कंपॅटिबिलिटी लेवेल्ज़. दीज़ रेग्युलेशन्स ऑल्सो डिफाइन थे मिनिमम पवर फॅक्टर रिक्वाइयर्ड फॉर थे एक्विपमेंट कनेक्टेड तो सिंगल फेज़ सप्लाइ. देर्फोर, थे ड्राइव्स अरे रेकमेंडेड वित फ्रंट एंड पफ्क (पवर फॅक्टर करेक्षन) कन्वर्टर्स तो इनक्रीस थे पवर कन्वर्षन एफीशियेन्सी आंड तो मीट थे इंटरनॅशनल स्टँडर्ड्स फॉर पवर क्वालिटी, सच आस इयीक-61000-3-2. थे रिसर्च इन पवर कन्वर्टर्स हास डेवेलप्ड थे कीं इंटेरेस्ट ऑफ रिसर्चर्स इन स्पेशल मशीन्स, विच हास बिन डेवेलप्ड इन लाते नाइंटींत सेंचुरी. ब्रुषलेषस डीसी मोटर, पर्मनेंट साइंकरनस मोटर, साइंकरनस रिलक्टेन्स मोटर आंड स्विच्ड रिलक्टेन्स मोटर (स्र्म) अरे सम ऑफ थे मोटर्स, विच अरे सीकिंग थे अट्रॅक्षन फॉर नंबर ऑफ अप्लिकेशन्स.

तीस वर्क एम्स अट थे डेवेलपमेंट ऑफ थे पवर फॅक्टर करेक्षन कन्वर्टर्स फॉर फीडिंग स्र्म ड्राइव आस आ कॉस्ट एफेक्टिव सल्यूशन फॉर लो पवर हाउशोल्ड अप्लिकेशन्स. थे कॉस्ट आंड एफीशियेन्सी अरे टू मोस्ट इंपॉर्टेंट आस्पेक्ट्स, विच प्ले आ वाइटल रोल इन थे डिज़ाइन ऑफ ड्राइव्स फोकसिंग टुवर्ड्स हाउशोल्ड्स अप्लिकेशन्स सच आस फँस, वॉटर पंप्स, वॅक्यूम क्लीनर, वॉशिंग मशीन एट्सेटरा. स्र्म हास सेलीयेंट पोले कन्स्ट्रक्षन सच तट थे स्टॅटर इस प्रोवाइडेड वित कॉन्सेंट्रेटेड वाइंडिंग्स, विच अरे एग्ज़ाइटेड थ्रू मिड-पॉइंट कन्वर्टर, सीक्वेन्षियली. थे रोटर इस मेड उप ऑफ लॅमिनेटेड मॅग्नेटिक मेटीरियल्स आंड फ्री फ्रॉम अन्य सॉर्ट ऑफ वाइंडिंग. स्र्म हास मानी अड्वांटेजस सच आस हाइ टॉर्क-वॉल्यूम रेशियो, फास्ट डाइनमिक रेस्पॉन्स, लो मॅन्यूफॅक्चरिंग कॉस्ट आंड वाइड स्पीड रंगे.

तीस वर्क एम्स अट थे डेवेलपमेंट ऑफ थे पवर फॅक्टर करेक्षन कन्वर्टर्स फॉर फीडिंग स्र्म ड्राइव आस आ कॉस्ट एफेक्टिव सल्यूशन फॉर लो पवर हाउशोल्ड अप्लिकेशन्स. थे कॉस्ट आंड एफीशियेन्सी अरे टू मोस्ट इंपॉर्टेंट आस्पेक्ट्स, विच प्ले आ वाइटल रोल इन थे डिज़ाइन ऑफ ड्राइव्स फोकसिंग टुवर्ड्स हाउशोल्ड्स अप्लिकेशन्स सच आस फँस, वॉटर पंप्स, वॅक्यूम क्लीनर, वॉशिंग मशीन एट्सेटरा. स्र्म हास सेलीयेंट पोले कन्स्ट्रक्षन सच तट थे स्टॅटर इस प्रोवाइडेड वित कॉन्सेंट्रेटेड वाइंडिंग्स, विच अरे एग्ज़ाइटेड थ्रू मिड-पॉइंट कन्वर्टर, सीक्वेन्षियली. थे रोटर इस मेड उप ऑफ लॅमिनेटेड मॅग्नेटिक मेटीरियल्स आंड फ्री फ्रॉम अन्य सॉर्ट

ऑफ वाइंडिंग. स्र्म हास मानी अड्वांटेजस सच आस हाइ टॉर्क-वॉल्यूम रेशियो, फास्ट डाइनमिक रेस्पॉन्स, लो मॅन्यूफॅक्चरिंग कॉस्ट आंड वाइड स्पीड रंगे.

थे सेलेक्षन ऑफ सूटबल पफ्क कन्वर्टर फॉर पर्टिक्युलर अप्लिकेशन डिपेंड्स अपॉन वेरियस आस्पेक्ट इंक्लूडिंग रेटिंग ऑफ स्र्म मोटर, वोल्टेज आंड करेंट रेटिंग ऑफ सेमिकंडक्टर डिवाइसस, टोटल नंबर ऑफ कॉंपोनेंट काउंट्स, रिक्काइर्मेंट ऑफ टू ईक्कल आउटपुट वोल्टएजस, गॅल्वॅनिक आइसोलेशन, कॉस्ट आंड एफीशियेन्सी ऑफ थे ओवरॉल सिस्टम. आउट ऑफ थे अवेलबल पफ्क कन्वर्टर कॉनफिगरेशन्स, थे रेकमेंडेड पफ्क कन्वर्टर्स फॉर थे प्रपोज़्ड स्र्म ड्राइव, अरे क्लासिफाइड इंटो फाइव डिफरेंट केटेगरीस ऑफ नों-आइसोलेटेड सिंगल आउटपुट पफ्क कन्वर्टर्स, नों-आइसोलेटेड ड्युयल आउटपुट पफ्क कन्वर्टर्स, आइसोलेटेड सिंगल आउटपुट पफ्क कन्वर्टर्स, आइसोलेटेड ड्युयल आउटपुट पफ्क कन्वर्टर्स आंड बरिडगेलएशस पफ्क कन्वर्टर्स. अमॉंग देम ड्युयल आउटपुट पफ्क कन्वर्टर्स अरे मेन्ली फोकस्ड आस पेर थे सिस्टम रिक्काइर्मेंट, आस टू ईक्कल आउटपुट वोल्टएजस अरे रिक्काइयर्ड तो फीड थे मिड-पॉइंट कन्वर्टर फेड स्र्म ड्राइव. इन तीस वर्क, पफ्क कन्वर्टर्स अरे डिज़ाइंड तो ऑपरेट इन ड्क्म, तो ओब्टेन इन्हेरेंट पवर फॅक्टर करेक्षन अट सप्लाइ मैंस. आस थे वोल्टेज फॉलोवर अप्रोच इस कन्सिडर्ड, देर्फोर, सेन्सर रिक्काइर्मेंट इस रेड्यूस्ड तो वन वोल्टेज सेन्सर, विच रेड्यूसस थे सिस्टम कॉस्ट.

थे मेजर आस्पेक्ट ऑफ थे वर्क, इंक्लूड्स सिंप्लिसिटी इन कंट्रोल आस टू ईक्कल आउटपुट वोल्टएजस अरे जेनरेटेड तो फीड थे मिड-पॉइंट कन्वर्टर फेड स्र्म ड्राइव विदाउट अन्य वोल्टेज बॅलेन्सिंग लूप. थे कन्वर्टर कॉनफिगरेशन्स प्रपोज़्ड फॉर थे स्र्म ड्राइव, अरे फीचर्स वित न्यूट्रल पॉइंट न तो जेनरेट, विच हास रेड्यूस्ड थे स्ट्रेस अक्रॉस थे सेमिकंडक्टर स्विचस. मोरोवर, थे सेलेक्टेड ड्क्म ऑफ ऑपरेशन वाइया वोल्टेज फॉलोवर अप्रोच रिक्काइर्स सिंपल कंट्रोल तो ओब्टेन इन्हेरेंट पवर फॅक्टर करेक्षन अट इनपुट साइड. इन तीस टेक्नीक, पफ्क इस ओब्टेंड ड्यू तो डिसकंटिन्युवस इनडक्टर करेंट मोड ड्यूरिंग ईच स्विचिंग पीरियड. ड्यूरिंग तीस पीरियड, थे सर्क्यूट बिहेव्स आस आन एम्युलेटेड रेज़िस्टेन्स, आंड दस इन्हेरेंट वेव-शापिंग इस प्रोवाइडेड तो थे सर्क्यूट. थे कंट्रोल्ड डीसी लिंक वोल्टेज ओवर वाइड रंगे, डेलिवर्स एक्सलेंट स्पीड कंट्रोल, विच इस वेल डेमॉन्स्ट्रेटेड इन थे टेस्ट रिज़ल्ट्स. थे पर्फॉर्मेन्स ऑफ प्रपोज़्ड पफ्क कन्वर्टर्स फेड स्र्म ड्राइव इस वॅलिडेटेड ओं थे मॉडेल्स डेवेलप्ड इन मतलब/सिमुलिंक एन्वाइरन्मेंट. फर्दर, तो वॅलिडेट थे सिम्युलेशन रिज़ल्ट्स, आ लॅबोरेटरी प्रोटटाइप ऑफ पफ्क कन्वर्टर फेड स्र्म ड्राइव इस डेवेलप्ड. हवेवर, थे पर्फॉर्मेन्स एवॅल्यूयेशन ऑफ प्रपोज़्ड स्र्म डाइव इस कॅरीड आउट ड्यूरिंग डिफरेंट स्टेडी स्टेट आंड डाइनमिक कंडीशन्स. थे

वोल्टेज आंड करेंट वेविफॉर्म्स ऑफ डिफरेंट सर्क्यूट कॉंपोनेंट्स इंक्लूडिंग सर्क्यूट इनडक्टर, केपॅसिटर आंड सेमिकंडक्टर स्विचस अरे अनलाइज़्ड. थे प्रपोज़्ड पफ्क कन्वर्टर्स फेड स्र्म ड्राइव इस ऑल्सो टेस्टेड अंडर डिफरेंट सप्लाइ वोल्टेज फ्लक्चुयेशन कंडीशन्स, विच इस वेल डेमॉन्स्ट्रेटेड थ्रू टेस्ट रिज़ल्ट्स. थे आक्सेप्टेड पवर क्वालिटी इंडिसेस ऑफ दीज़ पफ्क कन्वर्टर्स फेड स्र्म ड्राइव अरे ऑल्सो एवॅल्यूयेटेड अट एसी मैंस. थे फाउंड इंडिसेस कंप्लाइ वित थे गिवन पवर क्वालिटी स्टँडर्ड इयीक 61000-3-2.

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AC	Alternating Current
ADC	Analog to Digital Converter
BL	Bridgeless
CCM	Continuous Conduction Mode
CF	Crest Factor
CRM	Critical Conduction Mode/Critical Current Mode
CSC	Canonical Switching Cell
DAC	Digital to Analog Converter
DBR	Diode Bridge Rectifier
DC	Direct Current
DCM	Discontinuous Conduction Mode
DF	Distortion Factor
DPF	Displacement Power Factor
DSP	Digital Signal Processor
EMF	Electro Magnetic Force
EMI	Electro Magnetic Interference
IEC	International Electrotechnical Commission
IGBT	Insulated Gate Bipolar Transistor
I/O	Input/Ouput
HFT	High Frequency Transformer
LC	Inductor Capacitor
PCB	Printed Circuit Board
PF	Power Factor
PI	Proportional Integral
PMBLDC	Permanent Magnet Brushless DC
PWM	Pulse Width Modulation
PFC	Power Factor Correction
RMS	Root Mean Square
RTI	Real Time Interface
SC	Switched Capacitor
SEPIC	Single Ended Primary Inductance Converter

SRM	Switched Reluctance Motor
THD	Total Harmonic Distortion
UPF	Unity Power Factor
ZVS	Zero Voltage Switching

LIST OF SYMBOLS

C_1, C_{i1}, C_{i2}	Capacitance of Input Side Intermediate Capacitors (F)
C_2, C_{21}, C_{22}	Capacitance of Output Side Intermediate Capacitors (F)
C_{dc1}, C_{dc2}	Capacitance of DC Link Capacitors (F)
C_f	Capacitance of Filter Capacitor (F)
C_{fmax}	Maximum Capacitance of Filter Capacitor (F)
D_{max}	Maximum Duty Ratio
D_{min}	Minimum Duty Ratio
f_c	Filter Cut-off Frequency (Hz)
f_L	Line Frequency (Hz)
f_{sw}	Switching Frequency (Hz)
I_{dc}	DC Link Current (A)
$i_{A,}$ $i_{B,}$ $i_{C,}$ i_D	Phase Currents of SRM
i_{Li}, i_{Li1}, i_{Li2}	Input Side Inductor Current (A)
i_{Lo}, i_{Lo1}, i_{Lo2}	Output Side Inductor Current (A)
i_{sw}, i_{sw1}, i_{sw2}	PFC Converters Switch Current (A)
i_s	Drive Input Current (A)
I_m	Input Peak Current (A)
K_{pv}, p_{pv}	Proportional Gain for Voltage Controller
K_{iv}, p_{iv}	Integral Gain for Voltage Controller
L_f	Filter Inductor (H)
L_i, L_{i1}, L_{i2}	Inductance of Input Side Inductor (H)
L_m, L_{m1}, L_{m2}	Magnetizing Inductance of High Frequency Transformer (H)
L_s	Source Inductance
N	Speed of SRM (rpm)
N_1	Number of Primary Turns of High Frequency Transformer
$N_{2,}$ N_3	Number of Secondary Turns of Two Windings of High Frequency Transformer
N_2/ N_1	Transformation Ration of High Frequency Transformer
P_i	Instantaneous Power
P_{max}	Maximum Power (P_{max})
P_{min}	Minimum Power (P_{min})

P_{rated}	Rated Power of SRM Motor (W)
R_L	Emulated Load resistance (Ω)
T_e	Electromagnetic Torque of SRM Motor (Nm)
T_s	Sampling Time (sec)
T_{rated}	Rated Torque of SRM Motor (Nm)
v^*_{ref}	Reference Voltage (V)
v_e	Comparator Error Output Voltage
v_{cdc}	Controlled Output Voltage
V_{dc}	Total Sensed DC Link Voltage (V)
V_{dc1}, V_{dc2}	Voltage Across Two series Connected Output DC Link Capacitor (V)
V_{dcmax}	Maximum DC Link Voltage (V)
V_{dcmin}	Minimum DC Link Voltage (V)
v_s	Input Volatge (V)
V_{in}	Input Voltage After DBR (V)
V_m	Peak Value of Input Voltage After DBR (V)
v_{smin}	Minimum Supply Voltage (V)
v_{max}	Maximum Supply Voltage (V)
V_{c1}, V_{c1}	Voltage Across Intermediate Capacitors (V)
v_{sw}, v_{sw1}, v_{sw2}	Voltage Across Semiconductor Switches (V)
ω	Speed of SRM (rad/sec)
ω_L	Line Frequency (rad/sec)
Δi_{Li}, Δi_{L1}, Δi_{L2}	Ripple Current in Input Side Inductor (A)
Δi_{Lo}, Δi_{Lo1}, Δi_{Lo2}	Ripple Current in Output Side Inductor (A)
ΔV_c, ΔV_{c1}, ΔV_{c2}	Ripple Voltage Across Input Intermediate Capacitors (V)
ΔV_{c21}, ΔV_{c22}	Ripple Voltage Across Output Intermediate Capacitors (V)
η	Percentage of Ripple Current in Input Inductor (A)
χ, κ	Percentage of Ripple voltage Across Intermediate Capacitor (V)
δ	Percentage of Voltage Ripple across Two DC Link Capacitors (V)