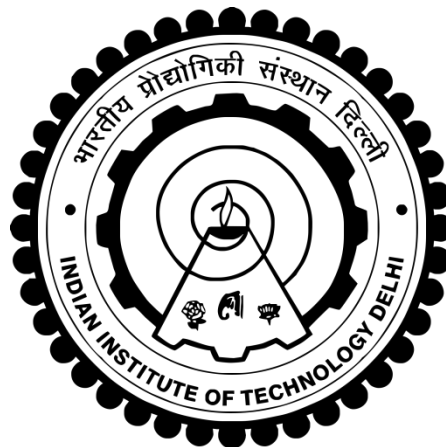


Development of Intelligent Maximum Power Point Tracking Techniques and Robust Control Algorithms for Grid Integrated Solar PV Energy Conversion System

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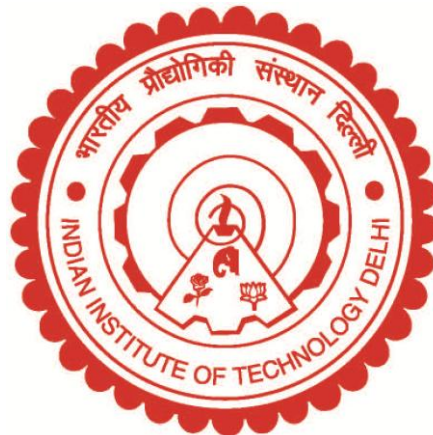
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Electrical Engineering Department

Submitted

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CERTIFICATE

It is certified that the thesis entitled “**Development of Intelligent Maximum Power Point Tracking Techniques and Robust Control Algorithms for Grid Integrated Solar PV Energy Conversion System,**” being submitted by **Mr. Nishant Kumar** for award of the degree of **Doctor of Philosophy** in the Department of Electrical Engineering, Indian Institute of Technology Delhi, is a record of the student work carried out by him under our supervision and guidance. The matter embodied in this thesis, has not been submitted for the award of any other degree or diploma.

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Nishant Kumar

ABSTRACT

The rapidly vanishing conventional energy sources (fossil fuels) have put an alarming energy crisis situation in front of the world. Moreover, the deteriorating environmental conditions have moved the world's attention towards nonconventional green energy sources. Amongst various available renewable energy sources, the solar PV (Photovoltaic) generation systems are gaining importance because of the abundance of sun, low maintenance, modular structure and the possibility of small generation plants at the rooftops. The solar PV generation systems can be broadly classified into two main categories, which are standalone and grid interfaced systems. The energy storage systems (generally batteries) are the inherent requirement of the standalone systems to match the instantaneous power balance, which adds to the extra cost and frequent maintenance in the standalone system. Therefore, battery-less grid interfaced solar PV generation systems are more preferred where the grid is available.

The increasing energy crisis has not only given promotions to renewable energy sources but also the efficient electrical equipment. Most of these equipment use power converters to achieve high efficiency and compact structure. However, the rapid increase in power converter based loads, has given rise to serious power quality problems such as poor power factor, harmonics in AC mains current, neutral current, voltage distortion etc. in the distribution network. Therefore, the energy crisis and the power quality problems are the two prime issues of the modern distribution network.

Moreover, the nonlinear power-voltage characteristic of solar PV array, which magnitude depends on uncertain solar irradiation and environmental temperature, creates a complex situation to operate the solar power generation at the maximum power point (MPP). In this situation, the panel situation and location also play an important role. The panel in open space, where no any obstacle is in between the sun and panel, their power-voltage characteristic of solar PV array consists of a single peak, and the change in solar irradiation impacts uniformly on every solar cell. However, if any obstacle is present in between the panel and sun, which shadow partially falls on the panel, their power-voltage characteristic of solar PV array consists of multiple peaks and the change in solar irradiation impacts non-uniformly (Partially-Uniformly) on every solar cell. Moreover, since the sun is continuous rotation, so the pattern of solar PV array characteristic also changes with time. In this situation, it requires a MPP tracking (MPPT)

or MPP searching algorithm, which quickly finds out the MPP operating point as well as forces the solar PV array to operate at MPP. Therefore, for optimal and efficient operation, a rapid and adaptive MPPT technique for uniformly shaded solar PV array condition as well as, a small population with quick conversion and accurate global MPP (GMPP) searching technique for partially shaded solar PV array conditions, are required, which are the prime issues of the modern maximum power extraction technique from the solar PV array.

Therefore, this research work presents a novel “self-adaptive hill climbing (SAHC)” MPPT algorithm for maximum power harvesting (MPH) from the uniformly shaded solar photovoltaic array, which has inherent decision taking and self-adaptive ability. The working principle of SAHC MPPT algorithm is based on three consecutive operating points on the power-voltage characteristic. These points, smartly detect the dynamic condition, as well as, in normal condition, search the maximum power peak (MPP) zone. Moreover, the used of a triangular analogy, decides the optimum operating position for the next iteration, which is responsible for quick MPP tracking as well as good dynamic performance.

Moreover, a novel “human psychology optimization (HPO)” algorithm is developed, which is based on psychological and mental states of an ambitious person. HPO algorithm is used for GMPP searching (GMPPS) in partially shaded solar PV array conditions. Here, the requirement of a population of the searching agent is less as well as, the convergence behavior is very fast and accurate, which are the essential requirements of the GMPPS algorithm.

In this work, after extracting maximum possible power from the solar PV array, by using DC-to-AC voltage source converter (VSC), it is fed to the local loads and the grid. For optimal operation of VSC, an efficient control technique is needed. The prime objective of the control technique is that the generated solar power is supplied to the nearby loads and, after satisfying the load demand, the rest power is supplied to the grid. However, when generated solar power is not sufficient for the load, then the load requirement is met by taking extra required power from the grid. In this process, the responsibilities of the control technique, are power factor correction, harmonics filtering and mitigation of other power quality issues.

This research work mainly focuses on the investigations of solar PV generation systems connected to the distribution network. The problem of voltage fluctuations, is quite common in the weak distribution network. Therefore, simple, intuitive and improved control algorithms for the PV inverters, are developed such that the PV inverter is capable of operating under a wide

range of voltage variation. The ANOVA kernel stochastic gradient descent (AKSGD) based adaptive control technique for weak grid environment, and decoupled adaptive vectorial filter (DAVF) based adaptive control for stiff grid environment, are developed for optimal integration of solar PV energy conversion system. All the MPPT algorithms and control techniques are simulated in MATLAB based environment, and the laboratory prototypes of them, are built to validate the simulation results. These PV inverters feed the sinusoidal currents at unity power factor with respect to PCC (Point of Common Coupling) voltage. In case of two-stage PV inverters, an adaptive DC link voltage-based control structure is presented, which has shown improvement in the performance in terms of reduction of switching losses, high-frequency ohmic losses and reduction of ripple content in the output current. Moreover, a single input fuzzy logic controller is developed for online gain tuning of PI controller, which improves the dynamic performance of the system. In addition, the solar PV energy is not available almost two third period of the day in a typical solar PV generating system, and its power converter is not utilized when there is no solar PV energy, and normally it is switched off in order to reduce its losses. This leads to poor utilization of the power converters involved in the grid interfaced solar PV system. Therefore, in order to improve the utilization factor of the solar PV generation system, multifunctional solar PV energy conversion system (SPECS) is proposed in this work. The multifunctional SPECS is the ones, which not only feeds the solar PV energy into the grid but also helps in power quality improvement at the PCC. In these multifunctional SECS, the grid-tied VSC not only serves for transferring the generated solar PV power into the distribution network but also for additional features such as harmonics mitigation, reactive power compensation, grid currents balancing etc.

The performances of MPPT algorithms, adaptive control techniques, online tuned PI controllers, are found satisfactory for all the features of the multifunctional SPECS, where all types of adverse situations are considered, such as different types of solar irradiation change condition, load unbalancing, grid over-voltage, under-voltage, voltage unbalance, and distorted grid voltage conditions. Moreover, the performance improvement is achieved in terms of less MPP tracking time, accurate achievement of true MPP, unity power factor operation in all types of adverse situations, reactive power support during zero solar irradiation, reduction of losses and mitigation of ripples in the grid currents.

सार

तेजी से लुप्त हो रहे पारंपरिक ऊर्जा स्रोतों (जीवाश्म ईंधन) ने दुनिया के सामने खतरनाक ऊर्जा संकट की स्थिति पैदा कर दी है। इसके अलावा, बिगड़ती पर्यावरणीय स्थितियों ने गैर-पारंपरिक हरित ऊर्जा स्रोतों की ओर दुनिया का ध्यान आकर्षित किया है। विभिन्न उपलब्ध अक्षय ऊर्जा स्रोतों के बीच, सौर पीवी (फोटोवोल्टिक) पीढ़ी प्रणाली सूरज की प्रचुरता, कम रखरखाव, मॉड्यूलर संरचना और छतों पर छोटे पीढ़ी के पौधों की संभावना के कारण महत्व प्राप्त कर रही है। सौर पीवी पीढ़ी प्रणालियों को मोटे तौर पर दो मुख्य श्रेणियों में वर्गीकृत किया जा सकता है, जो स्टैंडअलोन और ग्रिड इंटरफ़ेड सिस्टम हैं। ऊर्जा भंडारण प्रणाली (आमतौर पर बैटरी) स्टैंडअलोन सिस्टम की तात्कालिक शक्ति संतुलन से मेल खाने की अंतर्निहित आवश्यकता होती है, जो अतिरिक्त लागत और स्टैंडअलोन सिस्टम में लगातार रखरखाव को जोड़ती है। इसलिए, जहां ग्रिड उपलब्ध है, वहां बैटरी-कम ग्रिड इंटरफ़ेड सोलर पीवी जेनरेशन सिस्टम अधिक पसंद किए जाते हैं।

बढ़ते ऊर्जा संकट ने न केवल अक्षय ऊर्जा स्रोतों को बढ़ावा दिया है, बल्कि कुशल विद्युत उपकरण भी हैं। इनमें से अधिकांश उपकरण उच्च दक्षता और कॉम्पैक्ट संरचना प्राप्त करने के लिए बिजली कन्वर्टर्स का उपयोग करते हैं। हालांकि, पावर कन्वर्टर आधारित भार में तेजी से वृद्धि ने वितरण नेटवर्क में खराब बिजली का कारक, एसी मेन्स में हार्मोनिक्स, न्यूट्रल करंट, वोल्टेज विरूपण आदि जैसी गंभीर बिजली की गुणवत्ता की समस्याओं को जन्म दिया है। इसलिए, ऊर्जा संकट और बिजली की गुणवत्ता की समस्याएं आधुनिक वितरण नेटवर्क के दो प्रमुख मुद्दे हैं।

इसके अलावा, सौर पीवी सरणी की अरेखीय पावर-वोल्टेज विशेषता, जो परिमाण अनिश्चित सौर विकिरण और पर्यावरण के तापमान पर निर्भर करता है, अधिकतम शक्ति बिंदु (एमपीपी) पर सौर ऊर्जा उत्पादन को संचालित करने के लिए एक जटिल स्थिति बनाता है। इस स्थिति में, पैनल की स्थिति और स्थान भी एक महत्वपूर्ण भूमिका निभाते हैं। खुले स्थान में पैनल, जहां सूर्य और पैनल के बीच कोई बाधा नहीं है, सौर पीवी सरणी की उनकी शक्ति-वोल्टेज विशेषता में एक शिखर होता है, और सौर विकिरण में परिवर्तन हर सौर सेल पर समान रूप से प्रभाव डालता है। हालांकि, यदि पैनल और सूरज के बीच कोई बाधा मौजूद है, जो छाया आंशिक रूप से पैनल पर पड़ती है, तो सौर पीवी सरणी की उनकी शक्ति-वोल्टेज विशेषता में कई शिखर होते हैं और सौर विकिरण में परिवर्तन गैर-समान रूप से होता है (आंशिक रूप से एकरूप) हर सौर सेल पर। इसके अलावा, चूंकि सूरज निरंतर रोटेशन है, इसलिए सौर पीवी सरणी विशेषता का पैटर्न भी समय के साथ बदलता है। इस स्थिति में, इसे एमपीपी ट्रैकिंग (एमपीपीटी) या एमपीपी सर्चिंग एल्गोरिदम की आवश्यकता होती है, जो एमपीपी ऑपरेटिंग पॉइंट का पता लगाने के साथ-साथ सौर पीवी सरणी को एमपीपी पर संचालित करने के लिए मजबूर करता है। इसलिए, इष्टतम और कुशल संचालन के लिए, समान रूप से छायांकित सौर पीवी सरणी स्थिति के लिए एक त्वरित और अनुकूली एमपीपीटी तकनीक और साथ ही, त्वरित रूप से रूपांतरण और सटीक वैश्विक एमपीपी (जीएमपीपी) के साथ एक छोटी आबादी के लिए

आंशिक रूप से छायांकित सौर पीवी सरणी स्थितियों के लिए खोज तकनीक की आवश्यकता होती है।, जो सौर पीवी सरणी से आधुनिक अधिकतम बिजली निष्कर्षण तकनीक के प्रमुख मुद्दे हैं।

इसलिए, यह शोध कार्य समान रूप से छायांकित सौर फोटोवोल्टिक सरणी से अधिकतम बिजली कटाई (एमपीएच) के लिए एक उपन्यास "आत्म-अनुकूली पहाड़ी चढ़ाई (एसएचसी)" प्रस्तुत करता है, जिसमें अंतर्निहित निर्णय लेने और आत्म-अनुकूलन क्षमता है। एसएचसी एमपीपीटी एल्गोरिदम का कार्य सिद्धांत पावर-वोल्टेज विशेषता पर लगातार तीन ऑपरेटिंग बिंदुओं पर आधारित है। ये बिंदु, चालाकी से गतिशील स्थिति का पता लगाते हैं, साथ ही, सामान्य स्थिति में, अधिकतम पावर पीक (एमपीपी) जोन खोजते हैं।

इसके अलावा, एक त्रिकोणीय सादृश्यता का उपयोग, अगले पुनरावृत्ति के लिए इष्टतम ऑपरेटिंग स्थिति तय करता है, जो त्वरित एमपीपी ट्रैकिंग के साथ-साथ अच्छे गतिशील प्रदर्शन के लिए जिम्मेदार है। इसके अलावा, एक उपन्यास "मानव मनोविज्ञान अनुकूलन (एचपीओ)" एल्गोरिथ्म विकसित किया गया है, जो एक महत्वाकांक्षी व्यक्ति के मनोवैज्ञानिक और मानसिक स्थिति पर आधारित है। एचपीओ एल्गोरिथ्म का उपयोग जीएमपीपी खोज (जीएमपीपीएस) के लिए आंशिक रूप से छायांकित सौर पीवी सरणी स्थितियों में किया जाता है। यहां, खोज एजेंट की आबादी की आवश्यकता कम है और साथ ही, अभिसरण व्यवहार बहुत तेज और सटीक है, जो जीएमपीपीएस एल्गोरिथ्म की आवश्यक आवश्यकताएं हैं।

इस काम में, सौर पीवी सरणी से अधिकतम संभव बिजली निकालने के बाद, डीसी-टू-एसी वोल्टेज स्रोत कनवर्टर (वीएससी) का उपयोग करके, इसे स्थानीय भार और ग्रिड को खिलाया जाता है। वीएससी के इष्टतम संचालन के लिए, एक कुशल नियंत्रण तकनीक की आवश्यकता है। नियंत्रण तकनीक का मुख्य उद्देश्य यह है कि उत्पन्न सौर ऊर्जा को पास के लोड को आपूर्ति की जाती है और लोड की मांग को पूरा करने के बाद, शेष बिजली ग्रिड को आपूर्ति की जाती है। हालांकि, जब लोड के लिए उत्पन्न सौर ऊर्जा पर्याप्त नहीं होती है, तो ग्रिड से अतिरिक्त आवश्यक शक्ति लेकर लोड की आवश्यकता को पूरा किया जाता है। इस प्रक्रिया में, नियंत्रण तकनीक की जिम्मेदारियां, पावर फैक्टर सुधार, हार्मोनिक्स फ़िल्टरिंग और अन्य बिजली की गुणवत्ता के मुद्दों का शमन हैं।

यह शोध कार्य मुख्य रूप से वितरण नेटवर्क से जुड़ी सौर पीवी पीढ़ी प्रणालियों की जांच पर केंद्रित है। कमजोर वितरण नेटवर्क में वोल्टेज के उतार-चढ़ाव की समस्या काफी आम है। इसलिए, पीवी इनवर्टर के लिए सरल, सहज और बेहतर नियंत्रण एल्गोरिदम ऐसे विकसित किए गए हैं कि पीवी पलटनेवाला वोल्टेज की एक विस्तृत श्रृंखला के तहत काम करने में सक्षम है। कमजोर ग्रिड पर्यावरण के लिए एनोवा कर्नेल स्टॉचस्टिक ग्रेडिएंट डिसेंट (एकेएसजीडी) आधारित अनुकूली नियंत्रण तकनीक, और कठोर ग्रिड पर्यावरण के लिए अनुकूली सदिश फिल्टर (डीएवीएफ) आधारित अनुकूली नियंत्रण, सौर पीवी ऊर्जा रूपांतरण प्रणाली के इष्टतम एकीकरण के लिए विकसित किए गए हैं। सभी एमपीपीटी एल्गोरिदम और नियंत्रण तकनीक मेटलाब आधारित वातावरण में सिमुलेटेड हैं, और उनमें से प्रयोगशाला प्रोटोटाइप सिमुलेशन परिणामों को मान्य करने के लिए बनाए गए हैं। ये पीवी इनवर्टर पीसीसी (प्वाइंट ऑफ कॉमन कपलिंग) वोल्टेज के संबंध में एकता पावर फैक्टर में साइनसुइडल धाराओं को खिलाते हैं। दो-चरण पीवी इनवर्टर के

मामले में, एक अनुकूली डीसी लिंक वोल्टेज-आधारित नियंत्रण संरचना प्रस्तुत की जाती है, जिसने स्विचिंग घाटे में कमी, उच्च आवृत्ति वाले ओमिक नुकसान और आउटपुट वर्तमान में लहर सामग्री की कमी के संदर्भ में प्रदर्शन में सुधार दिखाया है। । इसके अलावा, पीआई नियंत्रक के ऑनलाइन लाभ ट्यूनिंग के लिए एक एकल इनपुट फ़ज़ी लॉजिक कंट्रोलर विकसित किया गया है, जो सिस्टम के गतिशील प्रदर्शन में सुधार करता है। इसके अलावा, सौर पीवी ऊर्जा दिन में लगभग दो तिहाई अवधि तक उपलब्ध नहीं होती है, जो कि सौर पीवी ऊर्जा पैदा करने वाली प्रणाली में होती है, और सौर पीवी ऊर्जा नहीं होने पर इसका पावर कन्वर्टर उपयोग नहीं किया जाता है, और आमतौर पर इसे कम करने के लिए इसे बंद कर दिया जाता है। इसके नुकसान। इसके चलते ग्रिड में अंतरित सौर पीवी प्रणाली में शामिल बिजली कन्वर्टर का खराब उपयोग होता है। इसलिए, सौर पीवी पीढ़ी प्रणाली के उपयोग कारक को बेहतर बनाने के लिए, इस काम में बहुक्रियाशील सौर पीवी ऊर्जा रूपांतरण प्रणाली (एसपीजीएस) प्रस्तावित है। मल्टीफ़ंक्शनल स्पेसिफिकेशन वे हैं, जो न केवल सौर पीवी ऊर्जा को ग्रिड में फीड करते हैं, बल्कि पीसीसी में बिजली की गुणवत्ता में सुधार में भी मदद करते हैं। इन बहुक्रियाशील एसईसीएस में, ग्रिड से बंधे वीएससी न केवल वितरण नेटवर्क में उत्पन्न सौर पीवी शक्ति को स्थानांतरित करने के लिए बल्कि हार्मोनिक्स शमन, प्रतिक्रियाशील बिजली मुआवजा, ग्रिड धाराओं संतुलन आदि जैसे अतिरिक्त सुविधाओं के लिए भी कार्य करता है।

एमपीपीटी एल्गोरिदम, अनुकूली नियंत्रण तकनीकों, ऑनलाइन ट्यून किए गए पीआई नियंत्रकों के प्रदर्शन, मल्टीफ़ंक्शनल स्पेस की सभी विशेषताओं के लिए संतोषजनक पाए जाते हैं, जहां सभी प्रकार की प्रतिकूल परिस्थितियों पर विचार किया जाता है, जैसे विभिन्न प्रकार के सौर विकिरण परिवर्तन की स्थिति, लोड असंतुलित होना, ग्रिड ओवर-वोल्टेज, अंडर-वोल्टेज, वोल्टेज असंतुलन और विकृत ग्रिड वोल्टेज की स्थिति। इसके अलावा, प्रदर्शन में सुधार कम एमपीपी ट्रैकिंग समय, सही एमपीपी की सटीक उपलब्धि, सभी प्रकार की विपरीत परिस्थितियों में एकता पावर फैक्टर ऑपरेशन, शून्य सौर विकिरण के दौरान प्रतिक्रियाशील शक्ति समर्थन, नुकसान में कमी और ग्रिड में तरंगों के शमन के लिए किया जाता है। धाराओं।

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LIST OF ABBREVIATIONS

ACOPO	Ant-Colony Optimization
ADC	Analog to Digital Converter
AFE	Average Function Evaluation
Ah	Ampere-hour
AKSGD	ANOVA Kernel Stochastic Gradient Descent
ANOVA	Analysis of variance
BBF	Butterworth Bandpass Filter
BPF	Band Pass Filter
CFL	Compact Florescent Lamp
C-H-R	Chien-Hrones-Reswich
CPU	Central Processor Unit
CSPDF	Change in shadow pattern in a different fashion
CSPSF	Change in shadow pattern in a similar fashion
DAVF	Decoupled Adaptive Vectorial Filter
DE	Differential Evolution
DPSO	Deterministic PSO
DSOGI	Damped SOGI
DSTATCOM	Distribution Static Compensator
DuSOGI	Dual SOGI
EPLL	Enhanced Phase Locked Loop
ES	European Standard
FACTS	Flexible Alternating Current Transmission Systems
FLC	Fuzzy Logic Controller
FLL	Frequency Locked Loop
FT	Fourier Transform
GMPP	Global Maximum Power Point
GMPPS	GMPP Searching
GMPPT	Global Maximum Power Point Tracking

GWO	Grey Wolf Optimizer
HC	Hill Climbing
HPO	Human Psychology Optimization
IAE	Integral of Absolute value of the Error
ILST	Improved Linear Sinusoidal Tracer
InC	Incremental Conductance
KF	Kalman Filter
LBP	Local Best Position
LMF	Least mean Fourth
LMI	Low to Medium Insolation
LMPP	Local Maximum Power Point
LMS	Least Mean Square
MAF	Moving Average Filter
MFA	Modified Firefly Algorithm
MHI	Medium to High Insolation
MP&O	Modified P&O
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MRF	Multiple Reference Frames
MSOGI	Modified SOGI
NLMS	Normalized LMS
NREL	National Renewable Energy Laboratory
OC	Orthogonal Component
P-V	Power-Voltage
P&O	Perturb and Observe
PCC	Point of Commune Coupling
PI	Proportional Integral
PID	Proportional Integral Derivative
PM	Prony's Method
PS-SPV	Partially Shaded SPV

PSO	Particle Swarm Optimization
PV	Solar Photovoltaic
PVFF	PV Feed-Forward
SA	Self Adaptive
SAHC	Self Adaptive Hill Climbing
SCR	Short Circuit Ratio
SECS	Solar Energy Conversion System
SFLC	Single-input Fuzzy Logic Controller
SFPI	Single-input Fuzzy- PI
SGD	Stochastic Gradient Descent
SO-SOGI	Second Order-SOGI
SOGI	Second Order Generalized Integrator
SPV	Solar Photovoltaic
SPS	Sim-Power System
SRC	Short Circuit Ratio
SRF	Synchronous Rotating Frame
SVF	Space Vector Filter
TA	Triangular Analogy
THD	Total Harmonic Distortion
UPF	Unity power factor
US-SPVA	Uniformly Shaded Solar PV Array
VSC	Voltage Source Converter

LIST OF SYMBOLS

α	Open circuit voltage rating of the PV array
α_1	Ideality factor of diode-1
α_2	Ideality factor of diode-2
β	PV array power rating at MPP
β'	Boltzmann constant
β''	Optimal duty cycle
β_{DC}	Loss component
$\beta(\alpha_{D_j}, t)$	Influence factor
η^s	Number of series solar cells
η^p	Number of parallel solar cells
η_f	Representation of error distance
v	Optimal step size
v'	Working irradiation
v^{ref}	Reference irradiation
μ_{lca}	Percentage peak to peak ripple allowed in the I_{pv}
μ_{lcv}	Percentage peak to peak ripple allowed in the V_{pv}
μ_r	Percentage peak to peak ripple allowed in the boost inductor
μ_{DC}	Percentage ripple allowed in the DC link voltage
μ	Excitement factor
μ_p	Designed parameter
$\mu_{pa}(n), \mu_{pb}(n), \mu_{pc}(n),$	Designed parameter of phase-a, phase-b and phase-c
ω	Grid frequency
ω'	PV array voltage rating at MPP
Ω	Leaky learning rate
Ω'	TA angle
ϵ	Change in power due to movement of one particle
$\hbar$	Length factor
ξ'	Length of baseline
ξ_{CI}	Californian efficiency
ξ_{Eu}	European efficiency

$\xi(\alpha_{D_j}, t)$	Consciousness factor
$\xi_{pa}, \xi_{pb}, \xi_{pc}$	Active weight of phase-a, phase-b and phase-c
ξ_p	Resultant estimated active weight component
ξ_{lp}	Active load power component
ξ	Feature map
σ	Slope of the baseline
$\sigma_{pa}(n)$	Autocorrelation factor
$\sigma_{pa}(n), \sigma_{pb}(n), \sigma_{pc}(n),$	Autocorrelation factor of phase-a, phase-b and phase-c
Φ	Angle of δ
Φ_p	Net active power component
δ	Length of the line
λ_1	Random numbers 1
λ_2	Random numbers 2
ε	Expected rate of change
Ψ	Spirit factor
ϑ_L	Lower limit of difference
ϑ_U	Upper limit of difference
τ and ς	Accelerating parameters
φ	Improved leakage component
$\phi_{ape}, \phi_{bpe}, \phi_{cpe}$	Prediction error of phase-a, phase-b and phase-c
ΔI_{PV}	Peak to peak ripple current
ΔI_{PVc}	Solar PV Current ripple
ΔV_{PVc}	Solar PV Voltage ripple
$\Delta V_{ref1new}$	New step size in iteration-1
ΔV_{PV}	Change in voltage
ΔV_{ref}	Fractional step change
ΔV_{refNew}	New step size
ΔP_{PV}	Change in power
ΔP	Change in power
$\Delta \mathcal{P}_{max}$	Maximum change in power during every iteration
$\Delta \mathcal{P}_{max, new}$	New maximum change in power during every iteration
A_a	Amplitude fundamental components

A_f	Fuzzy set
$A(n)$	Stability matrix
C_r	Ripple filter capacitance
C_{PV}	The link capacitor
d_{jk}^i	K^{th} searching agent of j^{th} population during i^{th} iteration
D_j^i	Set of variables of j^{th} population during i^{th} iteration
D_{max}	Maximum duty ratio
D_k^j	Duty cycle generated by k^{th} population during j^{th} iteration
D_{min}	Minimum duty ratio
D_{PV}	Duty cycle
D_{By}	Bypass diode
D_{BL}	Blocking diode
e_{DC}	DC link error
f_{sw}	Switching frequency
f_1 - f_7	Unimodal benchmark functions
f_8 - f_{13}	Under multimodal benchmark functions
f_{14} - f_{23}	Under fixed-dimension benchmark functions
$\ f\ $	Nearest integer to f
G_p	Proportional gain
G_I	Integral gain
h	Upper and lower hysteresis band
I_{mpp}	Current at MPP
I^s	Output current of the solar cell
I^H	Photovoltaic current of the solar cell
I_{sc}	Short circuit current
I^{1d}	Cell reverse saturation current of diode-1
I^{2d}	Reverse saturation current of diode-2
I^{sc}	Short circuit current of the solar cell
I_{PV}	Solar PV current
I_{mppA}	MPP current of PV array
I_{cbat}	Rating of battery charging current
I	Total number of iteration

$I_{PV}(D_k^j)$	SPV Current corresponding to the D_k^j
$I_{VSC\max,peak}$	Maximum peak current rating
i_{ga}, i_{gb}, i_{gc}	Grid current of phase-a, phase-b and phase-c
i_{La}, i_{Lb}, i_{Lc}	Load current of phase-a, phase-b and phase-c
I_{pv}	PV current
I_{Dpv}	Pv dynamic reflection component
$i_{ga}^*, i_{gb}^*, i_{gc}^*$	Reference grid currents of phase-a, phase-b and phase-c
I	Identity matrix
J	Total number of population
K	Total number of variables
κ^i	Short circuit current coefficients of temperature
κ^v	Open circuit voltage coefficients of temperature
K_G	Kernel function
K_{pf}	Fuzzy generated proportional gain
K_{If}	Fuzzy generated integral gain
k', k'', k_0	Clarke's transformation of i_{La}, i_{Lb} and i_{Lc}
k_a', k_a''	Output α, β component of DAVF for i_{La}, i_{Lb} and i_{Lc}
k_f	Filter constant
L	Large of η_f
L_{pf}	Large, output value for k_{pf}
L_{If}	Large value for k_{if}
L'	Lesson factor
L_o	Value of inductance
l', l'', l_0	Clarke's transformation of v_{sa}, v_{sb} and v_{sc}
l_a', l_a''	Output α, β component of DAVF for v_{sa}, v_{sb} and v_{sc}
m_{jk}^i	The best achieved value of k^{th} searching agent of j^{th} population upto the i^{th} iteration
M_{If}	Medium value for k_{if}
M_{pf}	Medium, output value for k_{pf}
M	Medium of η_f
N_p	Amplitude of input signals
N	Inspiration factor
P_{maxA}	MPP power of PV array

$P_{Present}$	Present power
P^1_{Past} or P^2_{Past}	Past power
P^i_{Dji}	Fitness function due to D_j^i for j^{th} population during i^{th} iteration
P_{max}	Maximum PV power
P_{min}	Minimum PV power
P_n	Nominal power
P_n	Nominal power
P_n	Amount of power
$P_{PV}(D_k^j)$	SPV Power corresponding to the D_k^j
q	Charge of an electron
R_{eq}	Equivalent resistance
$\mathcal{H}^{L \times L}$	$L \times L$ matrix of real number
R_r	Ripple filter resistance
R_{eq}	Equivalent resistance
r^p	Equivalent series resistance of the solar cell
r^{sh}	Equivalent parallel resistance of the solar cell
S	Self motivation Factor
S_k	Short circuit power
S_1	Gate pulse of switch 1 in VSC
S_2	Gate pulse of switch 2 in VSC
S_3	Gate pulse of switch 3 in VSC
S_4	Gate pulse of switch 4 in VSC
S_5	Gate pulse of switch 5 in VSC
S_6	Gate pulse of switch 6 in VSC
s_i and s_j	All samples
S_s	Input space
S_k	Short circuit power
S	Small of η_f
S_{pf}	Small, output value for k_{pf}
S_{if}	Small value for k_{if}
TL	Too large of η_f
TS_{pf}	Too small, output value for k_{pf}

TS	Too small of η_i
TL_{pf}	Too large, output value for k_{pf}
TS_{If}	Too small value for k_{if}
TL_{If}	Too large value for k_{if}
T_s	Settling time
T_{sw}	Switching time
t^w	Cell's working temperature
t^{ref}	Cell's reference temperature
U^t	Thermal voltage of the diode
U^{t1}	Thermal voltage of the diode-1
U^{t2}	Thermal voltage of the diode-2
U^{oc}	Open circuit voltage of the solar cell
U	Photovoltaic voltage of the solar cell
U_{eq}	Nominal voltage
u_a, u_b, u_c	Unit templates of phase-a, phase-b and phase-c
$u_a(n)$	Eigenvector
u_{aj}	Unit template for phase-a, during j^{th} iteration
$u_a(n-j)$	Unit template for phase-a, at $(n-j)^{th}$ instant
U_{eq}	Nominal voltage
U_f	Number of information
V_{oc}	Open circuit voltage
V_T	Optimum voltage
V_{mpp}	Voltage at MPP
V_{PV}	Solar PV voltage
VS_{If}	Very small value for k_{if}
VL_{If}	Very large value for k_{if}
V_{ref}	Reference voltage
$v'''_{\omega} v'''_{\beta}$	Output α , and β component of DAVF
$v'''_{\alpha\beta}$	Output $\alpha\beta$ component of DAVF
v_{sab}	PCC line a-b voltages
v_{sbc}	PCC line b-c voltages
V_x	Estimate the amplitude of phase voltages

V_{sa}, V_{sb}, V_{sc}	PCC phase voltage of phase-a, phase-b and phase-c
v_a, v_b, v_c	Filtered PCC phase voltage of phase-a, phase-b and phase-c
V_x	Amplitude of phase voltage
VS	Very small of η_f
VL	Very large of η_f
V_{DCref}	Reference DC link voltage
V_{DC}	DC link voltage
VL_{pf}	Very large, output value for k_{pf}
VS_{pf}	Very small, output value for k_{pf}
V_{nbat}	Voltage of the battery rating
V_{mppA}	MPP voltage of PV array
$V_{PV}(D_k^j)$	SPV Voltage corresponding to the D_k^j
V_s	Grid voltage
V_{OCA}	Maximum possible voltage
V_{DCmin}	Minimum voltage level of DC bus
V_{smin}	Lowest allowable AC side voltage
X_{eq}	Equivalent reactance
X_{eq}	Equivalent reactance
y_f^*	Defuzzified output