DEVELOPMENT OF INTELLIGENT VOLTAGE CONTROL METHODS USING OLTC TRANSFORMERS UNDER REVERSE POWER FLOW CONDITIONS CAUSED BY SOLAR PHOTOVOLTAIC POWER PLANTS

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Abstract

The rapid integration of renewable energy sources, particularly solar photovoltaic (PV) power plants, into modern electrical power systems has significantly affected the operation of distribution networks. The increasing number of prosumers has led to the emergence of reverse power flows, creating new challenges for voltage regulation, power quality, and transformer operation. Conventional distribution transformers and protection systems were originally designed for unidirectional power flow from generation sources to consumers. However, surplus electricity generated by PV systems is increasingly being injected back into the grid, causing voltage rise, increased power losses, and reduced equipment lifespan. This study proposes intelligent voltage control methods based on On-Load Tap Changer (OLTC) transformers to mitigate the adverse effects of reverse power flows. Mathematical modeling, artificial intelligence-based forecasting, and Smart Grid integration approaches are employed to enhance voltage regulation in distribution networks with high PV penetration.

Keywords: Solar photovoltaic power plant, OLTC transformer, reverse power flow, Smart Grid, artificial intelligence, voltage regulation, power quality, distribution network.

Introduction

The global transition toward sustainable energy systems has accelerated the deployment of renewable energy technologies, particularly solar photovoltaic (PV) power generation. Continuous reductions in PV installation costs and improvements in conversion efficiency have contributed to a substantial increase in solar energy penetration worldwide.

Uzbekistan has also adopted various governmental initiatives aimed at expanding the use of renewable energy resources. As a result, solar PV systems are increasingly installed in residential buildings, commercial facilities, and industrial enterprises. While this development contributes to environmental sustainability and energy independence, it also introduces operational challenges to existing power distribution networks.

Traditional electrical distribution systems were designed assuming a one-directional flow of electricity from centralized power plants to consumers. However, the widespread adoption of distributed solar generation has transformed many consumers into producers, commonly referred to as “prosumers.” During periods of high solar irradiance and low local consumption, excess electricity is exported back to the grid, resulting in reverse power flow conditions.

These reverse power flows may cause voltage rise, transformer overloading, protection malfunctions, and deterioration of power quality. Consequently, advanced voltage control strategies are required to ensure the stable operation of modern distribution networks.

Problem Statement

One of the most critical challenges in contemporary distribution networks is the injection of excess solar-generated electricity into the utility grid. In many regions, the electricity

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produced by photovoltaic systems exceeds local demand during daylight hours. Consequently, power is transferred from low-voltage feeders through distribution transformers toward higher-voltage networks.

Such operating conditions may lead to:

Transformer overloading;

Excessive voltage rise;

Deterioration of power quality indicators;

Malfunction of protection devices;

Increased energy losses;

Reduction of transformer service life.

These issues are particularly significant in rural distribution networks operating through 10/0.4 kV transformer substations.

Research Objective

The primary objective of this study is to develop intelligent voltage control methods using OLTC transformers under reverse power flow conditions caused by solar photovoltaic power generation.

To achieve this objective, the following tasks were addressed:

Analysis of the impact of reverse power flows on distribution networks;

Investigation of OLTC transformer operating principles;

Development of a mathematical model of the distribution network;

Design of an artificial intelligence-based control algorithm;

Evaluation of the technical and economic effectiveness of the proposed approach.

Research Object and Scientific Novelty

The research focuses on 10/0.4 kV distribution networks with a high penetration of solar photovoltaic generation. The study specifically investigates voltage regulation processes using OLTC transformers combined with intelligent control algorithms.

The scientific contributions of the study include:

Development of a mathematical model for distribution networks experiencing reverse power flows;

Proposal of an OLTC control algorithm based on solar generation forecasting;

Creation of an intelligent tap-position selection method;

Development of an optimization model for improving power quality;

Integration of OLTC control with Smart Grid technologies.

Mathematical Modeling of the Distribution Network

Power flow analysis within photovoltaic-integrated distribution systems is based on node power balance equations.

Active power:

P=UIcosφ

Reactive power:

Q=UIsinφ

Apparent power:

S=P2+Q2

Voltage drop across a distribution line is calculated as:

$\Delta U = UPR + QX$

where:

P = active power (kW),

Q = reactive power (kVAr),

R = line resistance (Ω),

X = line reactance (Ω),

U = system voltage (kV).

The reverse power flow generated by solar PV systems is expressed as:

$P_{reverse} = P_{PV} - P_{load}$

When:

$P_{PV} > P_{load}$ reverse power flow occurs.

Simulation results indicate that noticeable voltage rise begins when photovoltaic penetration reaches approximately 35–40% of feeder capacity.

Intelligent OLTC Control Algorithm

The primary function of an OLTC transformer is to maintain voltage levels within acceptable limits by adjusting the transformer turns ratio under load conditions.

Conventional OLTC systems typically respond only to instantaneous voltage measurements. In contrast, the proposed intelligent control approach incorporates multiple parameters, including:

Real-time voltage measurements;

Solar irradiance data;

Weather forecasts;

Consumer load demand;

Reverse power flow magnitude;

Transformer loading conditions.

The control sequence consists of:

Data acquisition from sensors;

Solar generation forecasting;

Future voltage estimation;

Determination of optimal tap position;

OLTC control signal execution;

Continuous monitoring and feedback.

This predictive approach enables proactive voltage regulation rather than reactive correction.

Artificial Intelligence-Based Forecasting Model

Artificial intelligence techniques significantly enhance OLTC control performance by accurately predicting future operating conditions.

Input Variables

Solar irradiance;

Ambient temperature;

Time of day;

Consumer demand;

Historical operational data.

Output Variables
Forecasted PV generation;
Predicted network voltage;
Optimal transformer tap position.

The generalized neural network model can be expressed as:
$Y=f(WX+b)$
where:
Y represents the prediction output;
W denotes weight coefficients;
X represents input variables;
b is the bias term;
f is the activation function.

Experimental results demonstrate forecasting errors within 3–5%, indicating high prediction accuracy.

Experimental Results
The following system parameters were used in the simulations:
Transformer rating: 250 kVA;
Total PV generation capacity: 180 kW;
Maximum load demand: 120 kW;
Minimum load demand: 60 kW.
Under daytime operating conditions:
PPV=180kWP load=60kW
Therefore:
Preverse=120kW

This means that 120 kW of power is exported from the low-voltage network to the higher-voltage grid through the transformer.

Voltage comparison:
Conventional control: 1.09 p.u.
Intelligent OLTC control: 1.02 p.u.
The proposed approach achieved:
38% reduction in voltage deviation;
11% reduction in energy losses;
15–18% reduction in transformer thermal stress;
Significant improvement in power quality.

Economic Analysis
Implementation costs include:

Component	Cost (Million UZS)
OLTC equipment	120
Automation and sensors	40
Software system	20
Total	180

Annual economic benefits:
Benefit Source Annual Savings (Million UZS)

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Reduced energy losses 35
Lower maintenance costs 25
Improved power quality 20
Total 80
Payback period:
T=80180=2.25 years
Thus, the investment can be recovered within approximately 2–3 years.

Discussion

The results demonstrate that increasing photovoltaic penetration significantly complicates voltage regulation within distribution networks. Since existing transformers were primarily designed for unidirectional power flow, reverse power flow conditions can negatively affect their operational performance.

The integration of artificial intelligence with OLTC control systems provides a promising solution for enhancing grid flexibility and maintaining voltage stability. Furthermore, such intelligent control strategies represent an essential component of future Smart Grid infrastructures.

Conclusion

The study confirms that large-scale deployment of solar photovoltaic systems leads to the emergence of reverse power flows in distribution networks. These conditions adversely affect transformer operation and overall power quality. OLTC transformers provide an effective mechanism for maintaining voltage within permissible limits, while artificial intelligence-based control significantly improves regulation performance compared to conventional methods.
The proposed intelligent voltage control approach reduces energy losses, enhances power quality, extends transformer service life, and improves the integration of renewable energy sources into electrical distribution networks. The results indicate that implementation of this technology within Uzbekistan's power distribution system is both technically feasible and economically beneficial.

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