ISSN (Online) 2278-1021
ISSN (Print) 2319-5940

IJARCCE

International Journal of Advanced Research in Computer and Communication Engineering

NCRICT-2017

Ahalia School of Engineering and Technology

Vol. 6, Special Issue 4, March 2017

Energy Efficiency Improvement in Distribution System Using Capacitor and Distributed Energy Resources

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Abstract: Reduction of loss is the critical function in a Distribution Management System (DMS). Commonly used reactive power (var) resource in Distribution Management System is switchable shunt capacitor banks. Today distributed energy resources (DER) are becoming another important var resource. This paper proposes an advanced loss reduction approach to achieve the optimal control coordination among capacitors and DERs which in turn reduce the losses and thereby increasing efficiency of DMS much greater than traditional practices. The proposed approach is developed on the basis of the detailed multi-phase distribution network modelling .The feasibility of the proposed method is demonstrated using MATLAB simulation. Finally, some experimental results are also presented to demonstrate the effectiveness and feasibility of the proposed approach.

Keywords: Distributed energy resources Distribution management system, Efficiency improvement, Harmonics reduction, Loss reduction approach, Reactive power flow control, Shunt capacitor banks. Voltage violation correction.

I. INTRODUCTION

In order to decrease the reactive component in the current flow, in distribution utilities, a regular practice is to place switchable capacitor banks at appropriate locations to supply reactive power (var) locally. As a result, the control of capacitor banks has been the focus of most existing loss reduction approaches [1]–[7]. In recent years, technology advances in distributed energy resources (DERs) which in turn have led to the proactive penetration of DERs in distribution systems for supplying reactive power. Many DERs allow the control of their var output within a certain range and thus become another important reactive power resource in the distribution circuit.
Voltage Var optimization techniques has been implemented in DMS from recent years [3]-[5].

Fuzzy logic is also implemented for better operation of distribution management system in power system [6]-[8].

Comparing to the on/off capacitor switching, the control of DER var output has two main advantages: (1) the capacitor switching is usually limited to 4–6 times per day in the operating practice, while the DER var control has no such restriction and can be conducted more often; (2) the DER var output can be adjusted in a continuous/small-amount manner that prevents/ corrects the over-/under-var compensation resulting from the discrete capacitor switching. These makes the DER reactive power control a promising means for reducing loss in addition to the capacitor switching.

The availability of DER var control presents both new opportunities and extra challenges in the system. Some research efforts have been devoted to integrate DERs in the loss reduction:

Based on authors' experience in applying multiphase model in the traditional loss reduction approach using capacitors only [1], this work attempts to achieve more advanced optimally coordinated control among DERs and multiple capacitors. Comparing to the existing approaches in DMS, contributions of this work are illustrated below:
- •Practical multi-phase model in the loss reduction method is used to reflect the unbalanced nature of the practical distribution network.
- •Improved power flow analysis accuracy.
- •The proposed approach achieves optimal coordinated control among multiple capacitors and DERs.
- •This work adopts a real-world distribution circuit to show the effectiveness of the proposed approach.

Overall, this paper presents a successful attempt in adopting the multi-phase distribution circuit model for loss reduction application, investigates the impact of balanced model on power flow accuracy, and achieves optimal coordinated control of various reactive power resources and demonstrates the results using MATLAB simulation software.
This paper is organized as follows: First, literature review is described in section II. Section III analyzes the

DOI 10.17148/IJARCCE

challenges in technical section faced by the advanced loss reduction technology. Section IV describes the proposed approach in detail. Section V provides the MATLAB Simulink model of the proposed approach. Section VI shows the results and section VII states the conclusion and also the future work.

II. LITERATURE REVIEW

Various methods for reducing the losses and different methodologies for controlling the var resources are explained in reference papers. In [1], loss reduction approach by integrating both DERs and Capacitors sre discussed with optimization and solution. A Volt Var optimization application is suggested then [2]. Reference [8] decouples the capacitor and DER reactive power control into two sub-problems that are solved in separate steps. The decision of capacitor switching is made first, based on which the DER reactive power output is determined. References [9] and [10] integrate the impact of DER power injection on the system loss into the optimal power flow (OPF) model. The solution of the OPF provides the DER reactive power settings. References [11]–[12] adopt metaheuristic techniques such as the genetic algorithm, ant colony algorithm, particle swarm optimization, and tabu search to solve volt/var optimization problems for the purpose of loss reduction.

III. CHALLENGES IN TECHNICAL SECTION

The objective of the loss reduction approach is to decrease the distribution system loss. The available controls include capacitor switching and DER reactive power output adjustment. Distribution systems in reality is having an unbalanced circuit construction and loading levels on three phases.

The unbalanced characteristics and various configurations of the distribution circuits exhibit in the following aspects:

- unbalanced device constructions;
- radial or meshed circuit configuration with single or multiple sources;
- various transformer connections, grounded or ungrounded, leading or lagging;
- star or delta load and capacitor bank connections;
- various voltage dependent load characteristics such as constant impedance load and constant power load;
- ganged or unganged control devices including capacitors and DERs.

As a result, major challenges in achieving an advanced loss reduction function is the realistic demonstration of the unbalanced distribution system characteristics and to achieve the optimal control coordination between DERs and Capacitors.

IV. SYSTEM MODELLING

This work proposes an advanced loss reduction approach developed on the basis of the detailed multi-phase distribution network modeling. This section describes the multi-phase distribution circuit modeling.

A. Multi-Phase Distribution System Modeling

This section illustrates representative distribution network device models based on single phase and multi-phase models.

(i) Multi-Phase Distribution Line: The distribution line is the backbone for a distribution system. The pi-equivalent model is used for both balanced and unbalanced line sections in this paper. Fig. 1 shows a pi-equivalent model for a three-phase distributed line section.

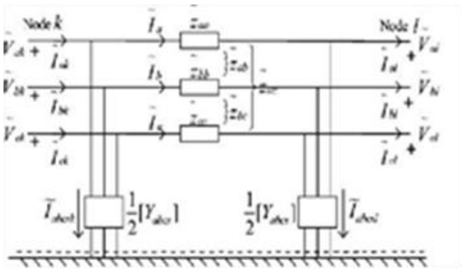


Fig 1. Three Phase Distribution Line Model

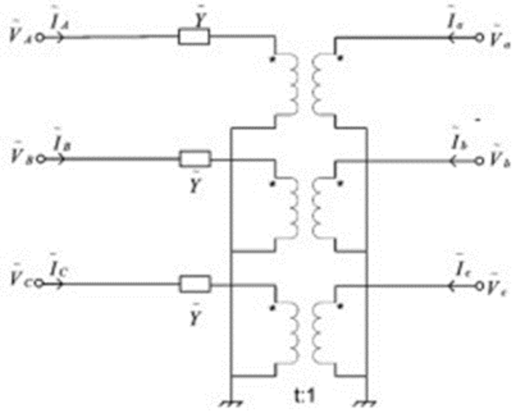


Fig 2. Transformer in Wye/Wye connection

(ii) Transformer configuration: Transformers in the distribution management system include substation transformers, transformers along the line section, and service transformers. These transformers may be balanced or unbalanced and present various configurations in practical distribution networks. All these transformer configurations are supported in this paper. Fig.2 shows a Wye/Wye grounded transformer example.

(iii) Load/Capacitor Connection and Modeling: In this paper, two types of load models is used. They are constant impedance and constant power loads. They are adopted to demonstrate different load voltage dependent characteristics. Fig. 3 shows a three-phase delta-connected load as an example and Fig.4 shows a three phase wye-connected capacitor with three unganged control variables. These variables can have values of 0 or 1, corresponding to the open or close switching of each phase in the network.

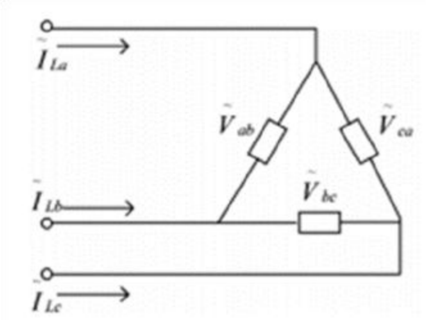


Fig 3. Three-Phase delta connected load

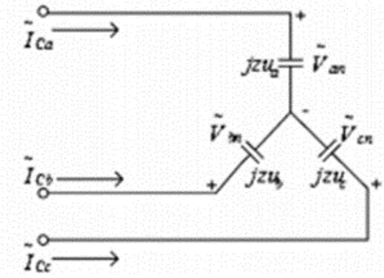


Fig 4. Wye connected capacitor bank

(iv Distributed Energy Resource: The capabilities of these DERs in controlling their var output are different, and some of these DERs have their var output controllable, they can operate at different assigned power factors.

Distributed energy resource (DER) systems are small-scale power generation or storage technologies (typically in the range of 1 kW to 10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system. DER systems in reality are characterized by high initial capital costs per kilowatt. DER systems also used as storage device and are often called as Distributed energy storage systems (DESS).

DER systems may include the following devices/technologies:
- Combined heat power (CHP), also known as cogeneration or trigeneration
- Fuel cells
- Hybrid power systems (solar hybrid and wind hybrid systems)
- Micro combined heat and power (MicroCHP)
- Microturbines
- Photovoltaic systems (typically rooftop solar PV)
- Reciprocating engines
- Small wind power systems
- Stirling engines
- Or a combination of the above. For example, hybrid photovoltaic, CHP and battery systems can provide full electric power for single family residences without extreme storage expenses.

Cogeneration: Distributed cogeneration sources use steam turbines, natural gas-fired fuel cells, microturbines or reciprocating engines to start the generators. The hot exhaust is then used for space or water heating, or to drive an absorptive chiller for cooling such as air-conditioning etc. In addition to natural gas-based schemes, distributed energy projects can also include other renewable and low carbon fuels.

Solar power: Photovoltaic, by far the most important solar technology for distributed generation of solar power, uses solar cells assembled into solar panels to convert sunlight into electricity.

Wind power: Wind turbines can be distributed energy resources or they can be built at utility scale. These have low maintenance and low pollution, but distributed wind unlike utility-scale wind has much higher costs than other sources of energy. As with solar, wind energy is variable and nondispatchable.

Hydro power: Hydroelectricity is the most widely used form of renewable energy and its potential has already been explored to a large extent or is compromised due to issues such as environmental impacts on fisheries, and increased demand for recreational access.

Waste-to-energy: Municipal solid waste (MSW) and natural waste, such as sewage sludge, food waste and animal manure will decompose and discharge methane-containing gas that can be collected and used as fuel in gas turbines or micro turbines to produce electricity as a distributed energy resource.

Energy storage: A distributed energy resource is not limited to the generation of electricity but may also include a device to store distributed energy (DE). Distributed energy storage systems (DESS) applications include several types of battery, pumped hydro, compressed air, and thermal energy storage.

V. SIMULATION MODEL

The simulation model for the proposed approach is shown below. Here zigzag phase shifting transformer blocks are implemented using three phase transformer with the primary winding connected in star or delta configurations and a configurable secondary winding. The model uses three single phase, three winding transformers.
The model also incorporates four three level bridge blocks and four (delta or star) phase shifting transformers. Switching frequency is fixed as 60 Hz.

Simulation model for three phase distribution line model is shown in Fig 5. Harmonic neutralization is obtained by use of appropriate phase shifts introduced by the zigzag connections (+7.5/-7.5 degree).

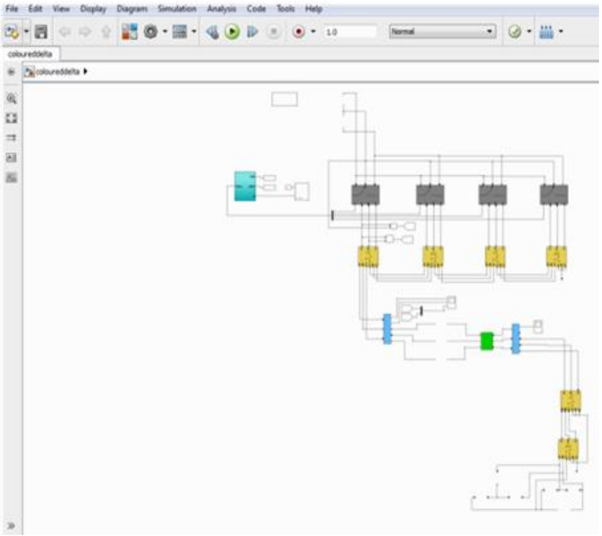


Fig 5.Three phase distribution line model

In this model, three level bridges are represented by grey coloured boxes. Yellow boxes indicate the zigzag phase shifting transformers with a phase shift of 7.5 degree. Firing pulse generator is shown in cyan colour. Light blue coloured box indicates three phase voltage and current measurement.

A three phase breaker is included in this model as shown in Fig 6. Delta connected load and star connected capacitor bank are also included in the circuit through the breaker.

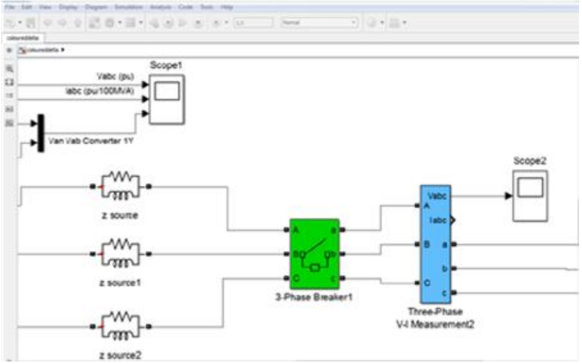


Fig 6. Three phase breaker in the simulation model.

VI. RESULTS AND DISCUSSION

Voltage and current output is shown in the Fig 7 and three phase AC signal obtained from bridges is shown in Fig 10. Fig 8 and Fig 9 shows voltage waveforms from load and two phases respectively.

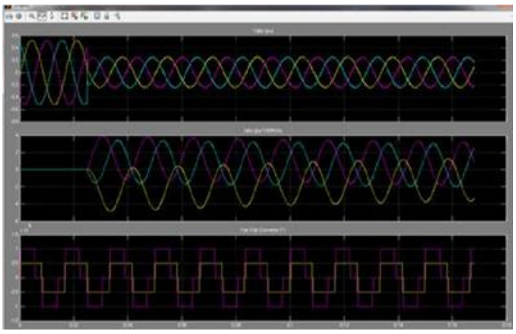


Fig 7. Voltage, Current and step output

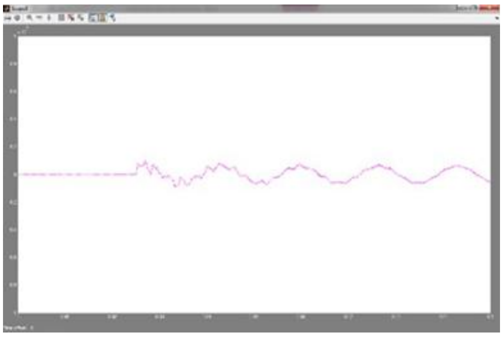


Fig 8. Voltage waveform from load

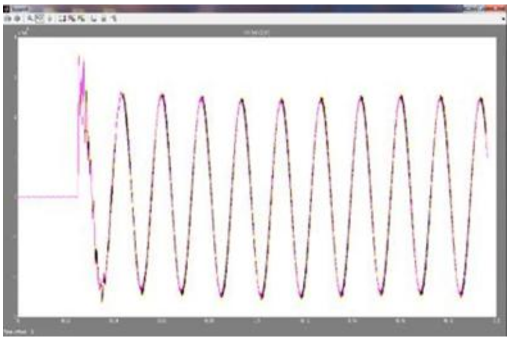


Fig 9. Waveforms of voltages from two phases

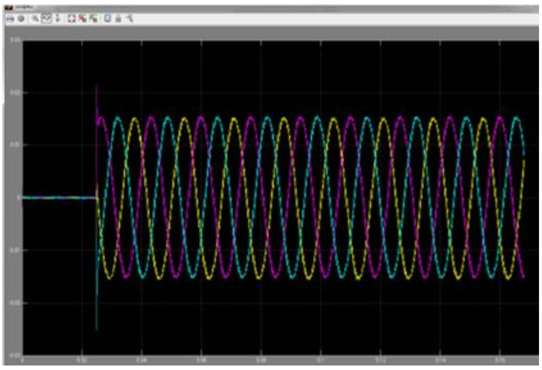
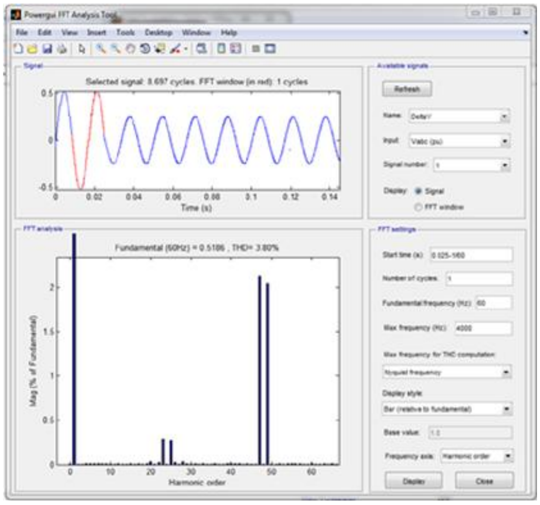


Fig 10. Three phase AC signal output from bridge

When breaker is closed, load consumes power and current begin to flow. Also voltage got reduced there by the loss. FFT Analysis is done to find out Total Harmonic Distortion (THD) which is shown in Fig 11. From the output it is clear that harmonic distortion is reduced to a great extent and thereby increasing efficiency.



Name: DeltaY
Input: Vabc (pu)
Signal number: 1
Display: ● Signal ○ FFT window
Start time (s): 0.025-160
Number of cycles: 1
Fundamental frequency (Hz): 60
Max frequency (Hz): 4000
Max frequency for THD computation: Nyquist frequency
Display style: Bar (relative to fundamental)
Base value: 1.0
Frequency axis: Harmonic order

Fig 11. FFT Analysis

VII. CONCLUSION

This paper presents an efficient and robust loss reduction approach based on the detailed multiphase unbalanced distribution circuit modeling. From the output, THD is reduced to a great extent there by increasing efficiency. The proposed approach is demonstrated using MATLAB Simulation. The test results shows the effectiveness of the optimally coordinated capacitor and DER control in loss reduction. The future work will include the OLTC and voltage regulators as the additional controllable devices.

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