International Journal of Engineering Science Invention
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 6 Issue 5|| May 2017 || PP. 51-62

Improvement of Power Quality in a low power network using STATCOM

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ABSTRACT:*Inthispaper,theauthorsproposeamethodofimprovementofpowerqualitybystaticsynchronouscompensators(STATCOMs)forlowvoltagesystem(singlephaseSTATCOMs)addedthefunctionofharmonicsuppression.Intheproposalmethod,theSTATCOMscontrolthevoltageofthedistributionsystemwithintheproperrangebycompensatingthereactivepower.Additionally,theyareoperatedasthefilteringfunctionandsuppressharmonicsofthevoltageofthedistributionsystem.ThefilteringgainisdeterminedbyPIcontrollingtheerrorbetweenthevoltagetotalharmonicdistortionofthepointvoltageattheinstallationofSTATCOMsandthetargetvalue.Inordertoverifythevalidityoftheproposalmethod,thenumericalcalculationsarecarriedoutbyusingananalyticalmodelofdistributionsystemwhichinterconnectedphotovoltaicgeneration systems. Simulation results show the eﬀect of improvement of power quality on both sides of voltage deviation andharmonics.*

KEYWORDS: *Harmonics; power quality; STATCOM; voltage control; voltage total harmonic distortion*

I. Introduction

In recent years, against a background of an environmen- tal problem and resource problem, the number of inter- connection of distributed generators (DGs) such as the photovoltaic generations (PVs) and wind power genera- tionshavebeenincreasing.However,theoutputsofthese DGs change rapidly with the influences of the weather, condition of location, etc. It may cause the voltage fluc- tuation in the distribution system. Therefore, it is con- cerned that the point voltages of distribution system change violently and they may deviate from the proper rangeforvoltage.Ontheotherhand,thereisalsoconcern about the deterioration of power quality of the distribu- tionsystemsuchastheincreaseofharmonics.Theseare thoughttobecausedbytheprogressofpowerelectronics technology and the increase of the number of intercon- nection of DGs for home. In general, to maintain the point voltages in the distribution system, the various control devices such as the load ratio controltransformer (LRT), the step voltage regulator (SVR), the static var compensator (SVC), and the static synchronous compen- sator(STATCOM)havebeenused.Moreover,theactive filter has been used to suppress harmonics in the distri- bution system. Most of these devices are installed at the high voltage system, and the various studies on the vol- tage management by them in the distribution system interconnected DGs have been done [1–4]. However, most of the DGs are generally installed in the lowvoltage

system and the number of them will be increasing more and more in the future. Therefore, it is considered that it may become more difficult to control the voltage in the lowvoltagesystemcompletelyby the devices installed at the high voltage system. To this problem, installing the voltagecontrol devices at the lowvoltage system has been proposed. For example, it has been reported aboutresearches of development of the compact STATCOM and the single-phase active filter[5–7].In the above back- ground, the authors have been proposed a voltagecontrol method by STATCOMs for low voltage system[8].

In this paper, the authors focus on that circuit con- figuration of STATCOM is the same as the active filter and propose a method of improvement of power quality by STATCOMs for low voltage system (single-phase STATCOMs) added the function of harmonic suppres- sion. In the proposal method, the STATCOMs control the voltage of the distribution system within the proper range by compensating the reactive power. Additionally, they are operated as the filtering function and suppress harmonics of the voltage of the distribu- tion system. The filtering gain is determined by PI con- trolling the error between the total harmonic distortion (THD) of the point voltage at the installation of STATCOMs and the target value. In order to verify the validity of the proposal method, the numerical cal- culations are carried out by using an analytical model of distribution system which interconnectedPVs.

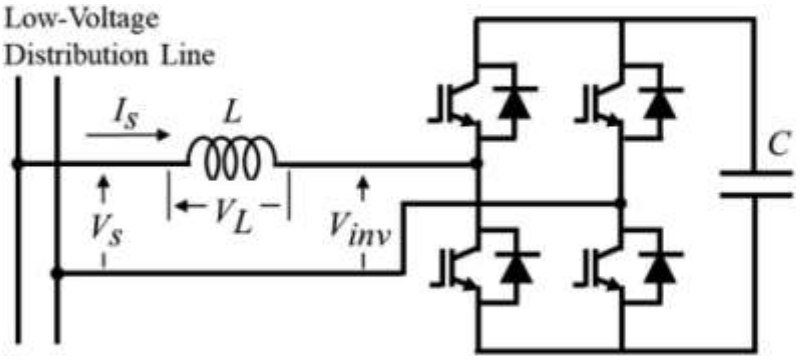


Figure 1. Main circuit of STATCOM for low voltage system.

II. STATCOM For Low Voltagesystem

Figure 1 shows the main circuit of STATCOM for low voltage system. It is a single-phase voltage typeinverter composed by switching devices such as IGBT, a DC- capacitor C, and an interconnected inductor L. By con- trolling the switching devices, it is possible to generate an AC waveform of any amplitude, frequency, and phase from the DC voltage charged in the capacitor. Figure 2 shows the generation principle of the reactive power by STATCOM. In Figure 2, $V_s$is the system voltage, $V_{inv}$is the output voltage of STATCOM, and $V_L$is the potential diff erence between $V_s$and V_{inv}. When $V_s$is larger than V_{inv}, the lagging reactive current is outputted in the side of the distribution system. In contrast, when $V_s$is smaller than V_{inv}, the leading reac- tive current is outputted. Therefore, STATCOM can absorb or supply the reactive power to maintainthe voltage at the installation point by controlling V_{inv}.

On the other hand, the circuit configuration of the active filter is the same as STATCOM which is a voltagetype inverter. In this study, a voltage detection system is usedasacontrolmethodoftheactivefilter[9].Inthisway, the compensating current reference i_h* is given by(1).

i_h^m¼ $K_v \cdot v_h$ (1)

where$v_h$istheharmonicsintheinstallationpointvoltage and $K_v$is a control gain. The active filter behaves as aresistanceof1/K_v(Ω)toharmonicvoltage.Itispossible to suppress the spread of harmonics phenomenon by setting the gain $K_v$accurately.

III. Voltage Control Bystatcoms

Figure 3 shows the conceptual diagram of the sup- posed low voltage system. The supposed low voltage system is spread to left and right from the pole transformer. In this study, STATCOM for low voltage system is installed on each utility pole at both ends of the low voltage system. Moreover, the STATCOM can get the measurement information of the pole trans- former and another STATCOM from the power line communication. When the reverse power flow from PVs installed at the consumer is happened, the voltage rise will be occurred at the consumer caused by the reverse current flow of PVs through the service wire. In Japan, it is defined to maintain the consumer voltage of the low voltage system based on 100 V within 101 6 V. Therefore, the target voltage of STATCOMs must be set considering the voltage rise at the servicewire.

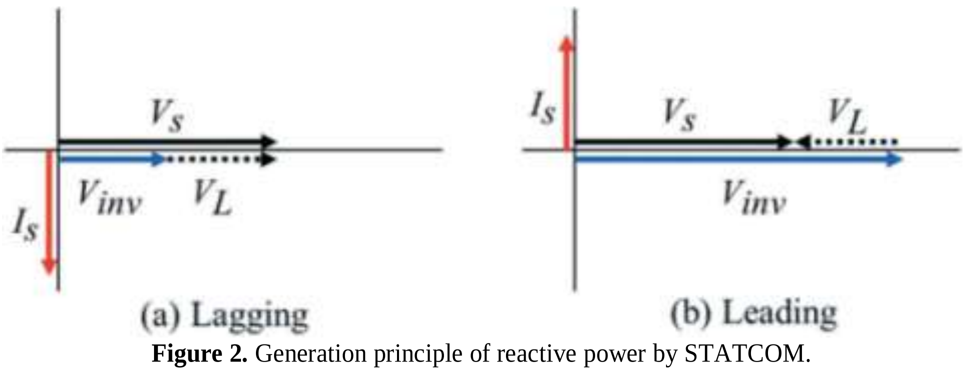


Figure 2. Generation principle of reactive power by STATCOM.

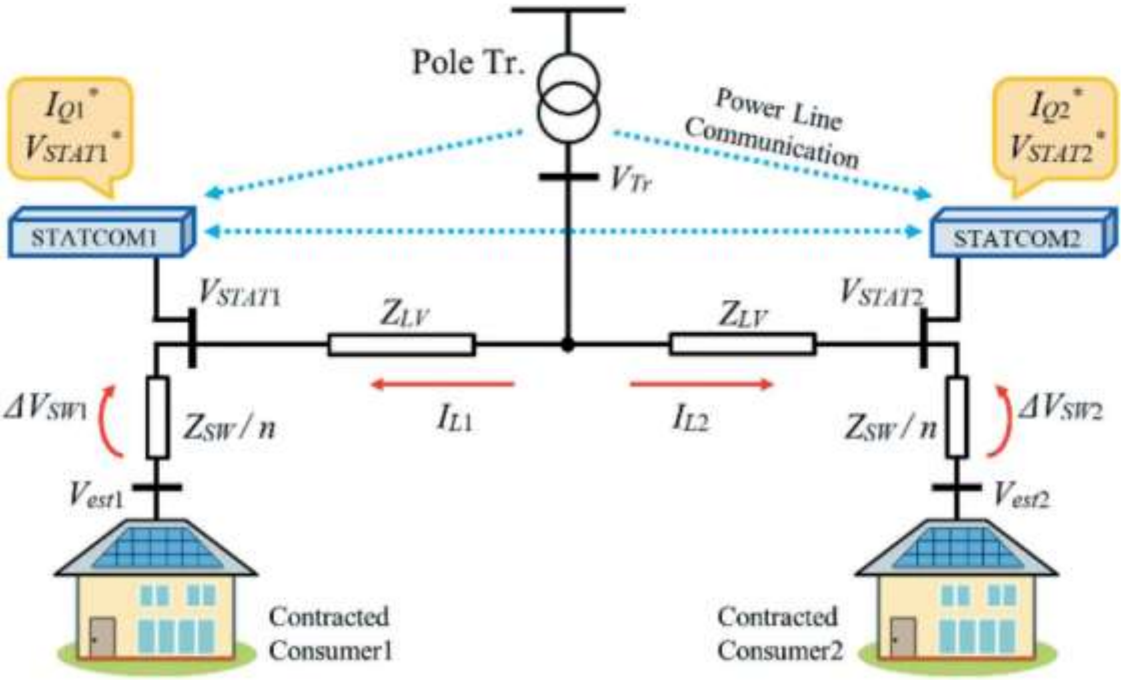


Figure 3. Conceptual diagram of low voltage system.

In this study, STATCOMs estimate the interconnec- tion point voltage of consumer and the reference reac- tive current is determined from the following steps.

[Step 1]

At first, contract plural consumers between the pole transformer and the installation point of STATCOM toone.

[Step 2]

Next,estimatetheinterconnectionpointvoltageofthe contracted consumer V_{est}. $V_{est}$is calculated by (2)–(4).

$$I_{Li} = (V_{Tr} - V_{STATi})/Z_{LV} \qquad (2)$$

$$\Delta V_{SWi} = (Z_{SW}/n) \cdot I_{Li} \qquad (3)$$

$$V_{esti} = V_{STATi} - \Delta V_{SWi} \qquad (4)$$

whereI_{Li}isacurrentflowingtothecontractedconsu- mer$i$,V_{Tr}isavoltageofthesecondarysideofthepole transformer, $V_{STATi}$is an interconnection pointvoltage of STATCOMi, $Z_{LV}$is the average impedance of low voltagedistributionline,Z_{sw}istheaverageimpedanceof servicewire,$n$isthenumberofcontractedconsumers,ΔV_{sw}isthechangeamountofvoltageattheservicewire, $V_{esti}$is the estimated interconnection point voltage of considering the voltage rise at the service wire.

V_{STAT}* is calculated by (5).

$$V_{STATi}^{*} = (V_{Target\_H}\ or\ V_{Target\_L}) + \sum \Delta V_{SWi} \qquad (5)$$

In this study, each STATCOM shares the control amount to reduce the total capacity of itself using the power line communication. The target voltage of STATCOM after sharing the control amount V_{STAT_share}* is calculated by(6).

V_{STATi_share*} ¼ P M i¼ V δV M STAT – þ V_{STATi} (6)

the contracted consumer*i*.

[Step 3]

the contracted consumeri.
[Step 3]
If Vestdeviates the target range of voltage deter- mine the target voltage of STATCOMVSTAT* where VSTATi_share* is the target voltage of STATCOMi after sharing the control amount and M is the number of STATCOMs installed in a low voltage system.

where V_{STATi}* is the target voltage of STATCOM*i*, $V_{Target_H}$and $V_{Target_L}$are upper and lower limit of the target range of voltage,respectively.

[Step 4]

[Step 5]
Finally, determine the reactive current reference IQ* after sharing the control amount of each STATCOM. IQ* is calculated by PI controlling the error of VSTAT_share* and VSTATas the following(7).

the contracted consumeri.
[Step 3]
If Vestdeviates the target range of voltage deter- mine the target voltage of STATCOMVSTAT*

where VSTATi_share* is the target voltage of STATCOMi after sharing the control amount and M is the number of STATCOMs installed in a low voltage system.
[Step 5]
Finally, determine the reactive current reference IQ* after sharing the control amount of each STATCOM. IQ* is calculated by PI controlling the error of VSTAT_share* and VSTATas the following(7).

$$I_{Qi}^{*} = K_{P1}(V_{STATi\_share*} - V_{STATi}) + K_{I1}\int (V_{STATi\_share*} - V_{STATi})dt \quad (7)$$

where IQi* is the reactive current reference of STATCOMi, KP1 is proportional gain, and KI1 is integral gain.

1. Proposed control method of STATCOMs is composed of two units, the voltage control unit and the harmonics control unit. In the voltage con- trol unit, the reactive current reference i_Q* is calcu- lated by PI controlling the error of the target voltage V_{STAT_share}*andtheinterconnectionpointvoltageof

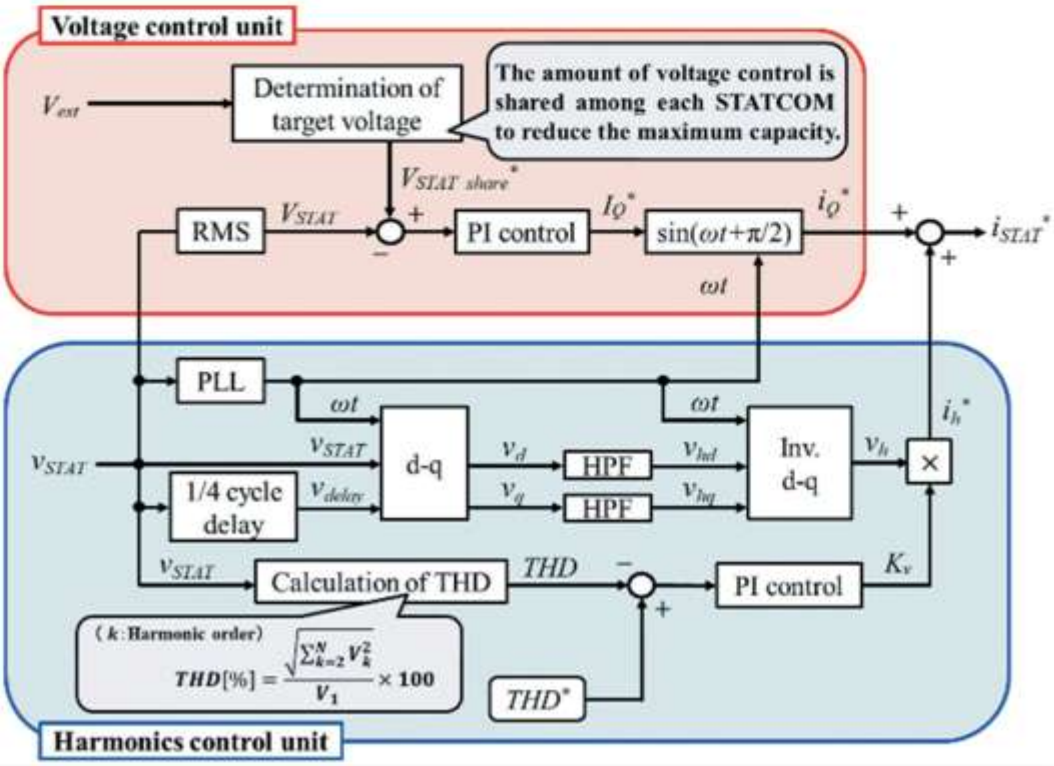


Figure 4. Block diagram of control circuit with filtering function.

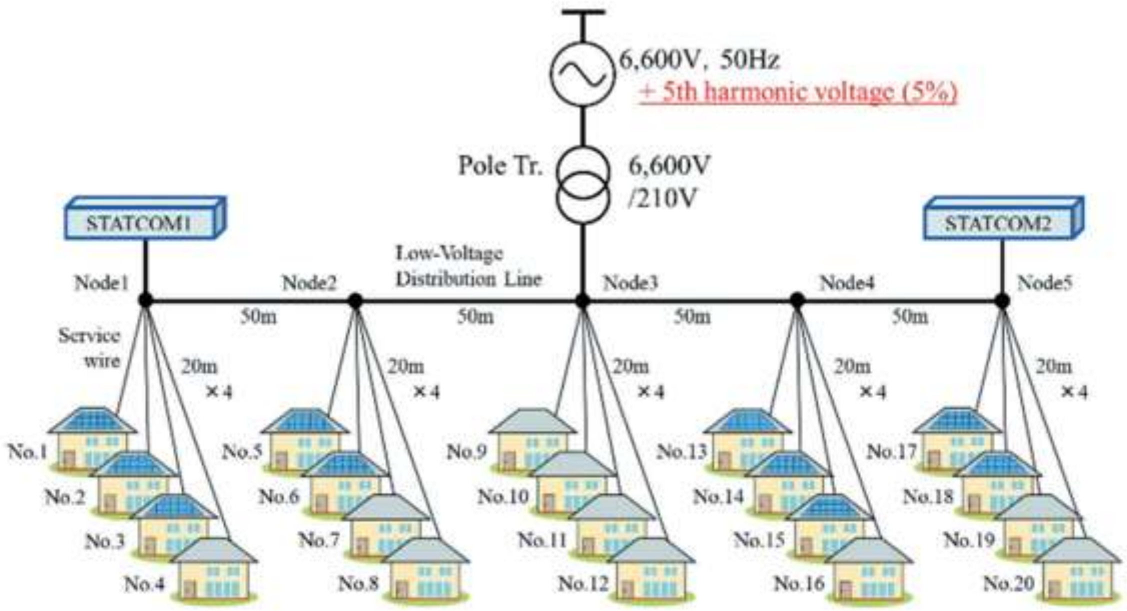


Figure 5. Analytical model of the distribution system.

Table 1. Simulationcondition

Content		Value
Tapofpoletransformer		6,600/210V
Properrange: $V_{Limit,H}/V_{Limit,L}$		214/190 V (1.07/0.95p.u.)
STATCOM	Target range: $V_{Target,H}/V_{Target,L}$	212/192 V (1.06/0.96 p.u.)
	TargetT.H.D: T.H.D*	3%
	Proportionalgain: K_{P1}, K_{P2}	2,2
	Integralgain: K_{I1}, K_{I2}	8,10
	Consumer	
		Peak load 1kW
	Peak outputofP.V.	4kW
Lowvoltage distributionline	Lengthbetweennodes	50m
	Impedance	0.313+ j0.264Ω/km
Servicewire	Length	20m
	[illegible]	[illegible] km

On the other hand, the compensating current refer- ence i_h* is calculated in the harmonics control unit, and the control principle is the same as the active filter. At first, the detected voltage $v_{STAT}$is transformed into the d-q coordinates, $v_d$and v_q. Then, the dc component of them which corresponds to the fundamental frequency

$$THD = \frac{\cdots}{k=2} \times 100 \qquad (8)$$

$$K_V = K_{P2}(THD^* - THD) + K_{I2}\int (THD^* - THD)\,dt \qquad (9)$$

where THD is the total harmonic distortion, V_1 is the fundamental voltage, $V_k$is the k-th harmonic voltage, K_{P2} is proportional gain, and K_{I2} is integral gain.
At last, the output current reference of STATCOM
i_{STAT}* is determined as the total value of i_Q* andi_h*,and

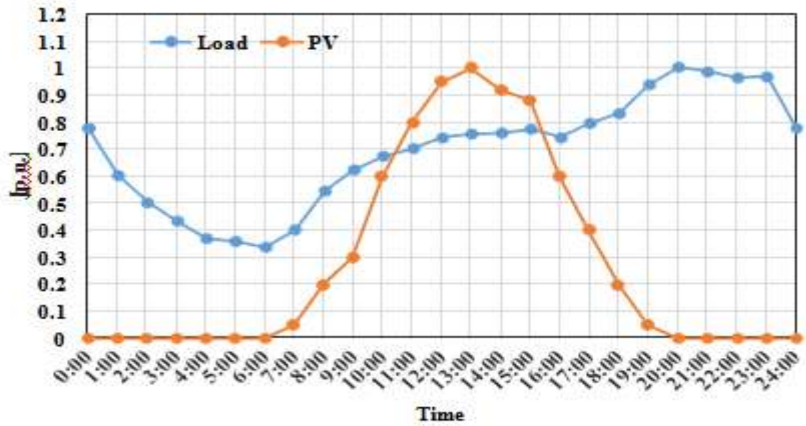


Figure 6. Input data (load curve and output of PV).

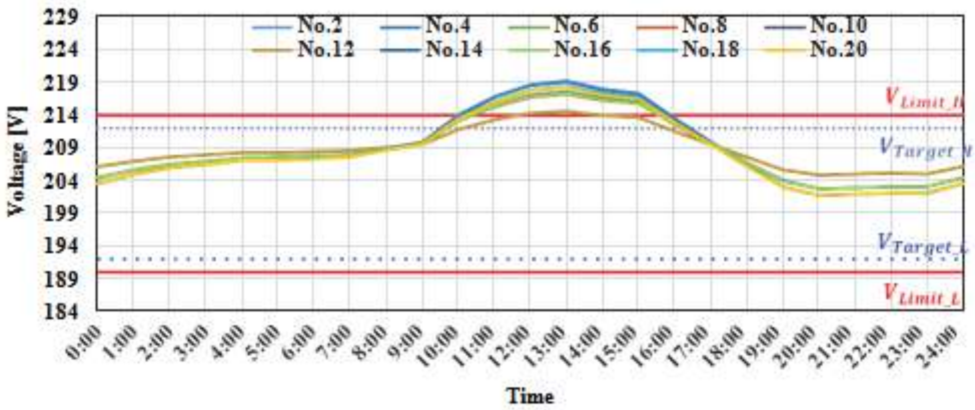


Figure 7. Consumer voltages without control.

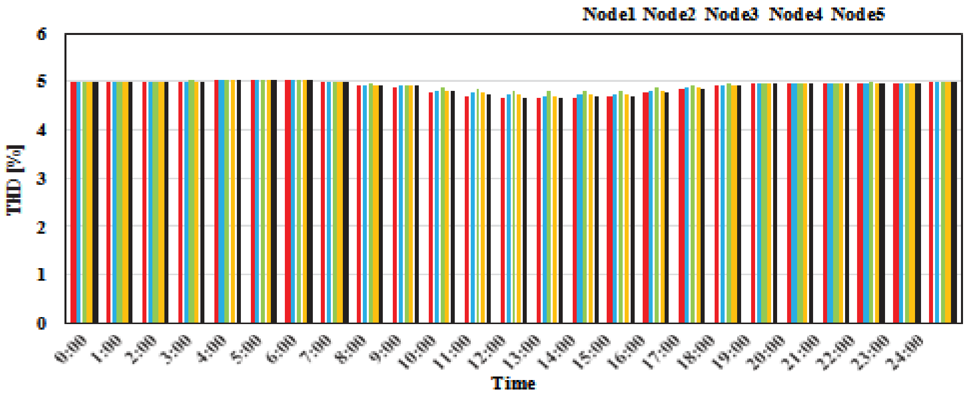
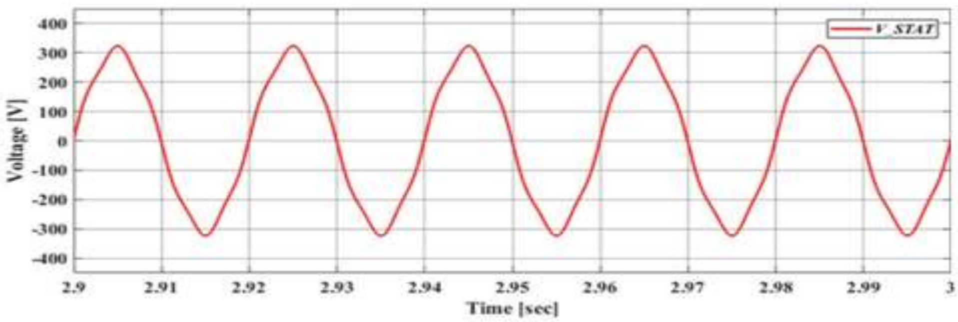
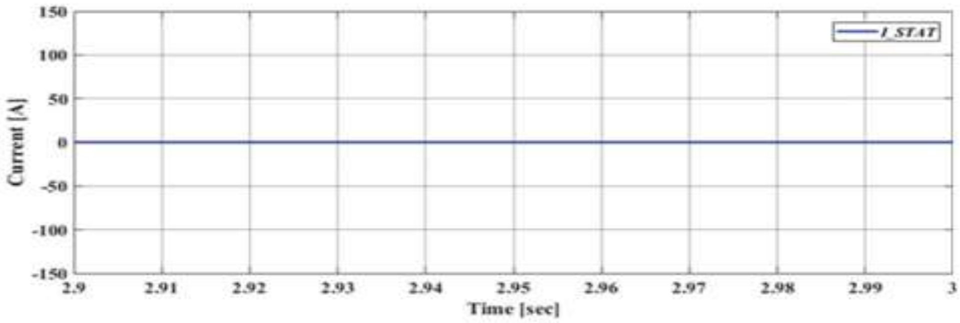


Figure8.THDofeachnodevoltagewithoutcontrol.(a)Interconnectionpointvoltage(node1voltage).(b)Outputcurrent.



(a) Interconnection point voltage (node1voltage)



(b) Outputcurrent

Figure 9. Waveforms of STATCOM1 at 13:00 without control.

given by (10). In this control method, STATCOM is oper- ated as the filtering function even when there is no voltage deviation in the low voltage system, and it is useful for the improvement of power quality throughout the day.

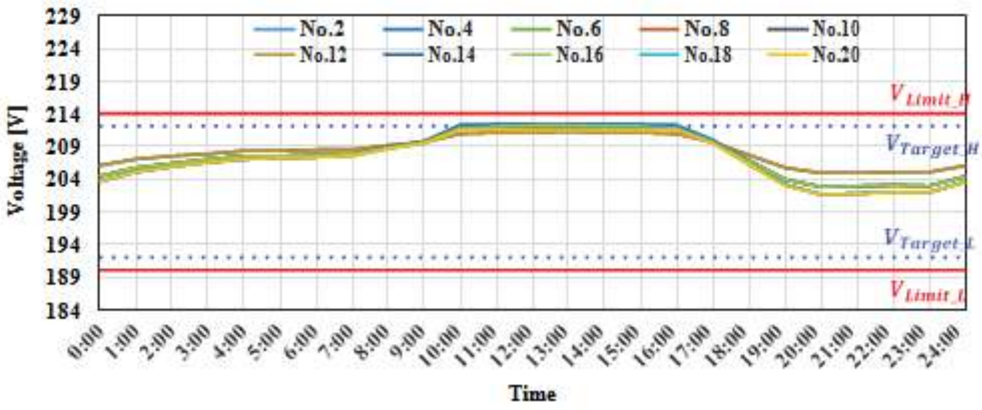


Figure 10. Consumer voltages with conventional control.

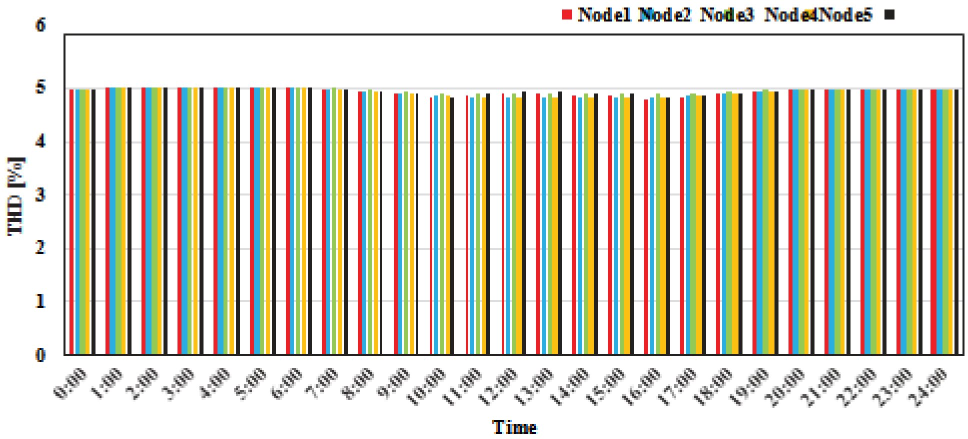


Figure 11. THD of each node voltage with conventional control.

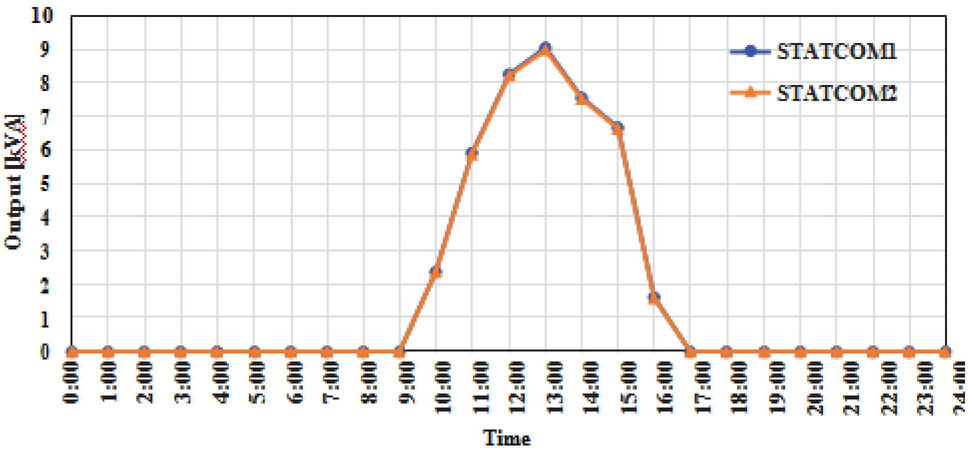
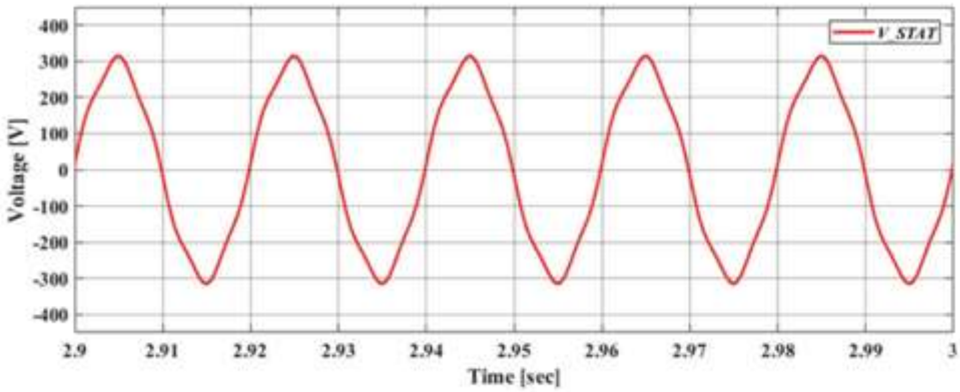
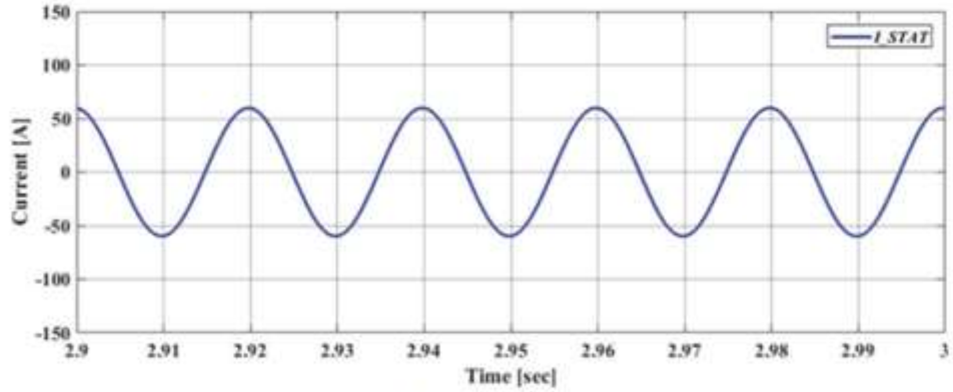


Figure12.OutputofSTATCOMswithconventionalcontrol.(a)Interconnectionpointvoltage(node1voltage).(b)Outputcurrent.



(a) Interconnection point voltage (node1voltage)



(b) Outputcurrent

Figure 13. Waveforms of STATCOM1 at 13:00 with conventional control.

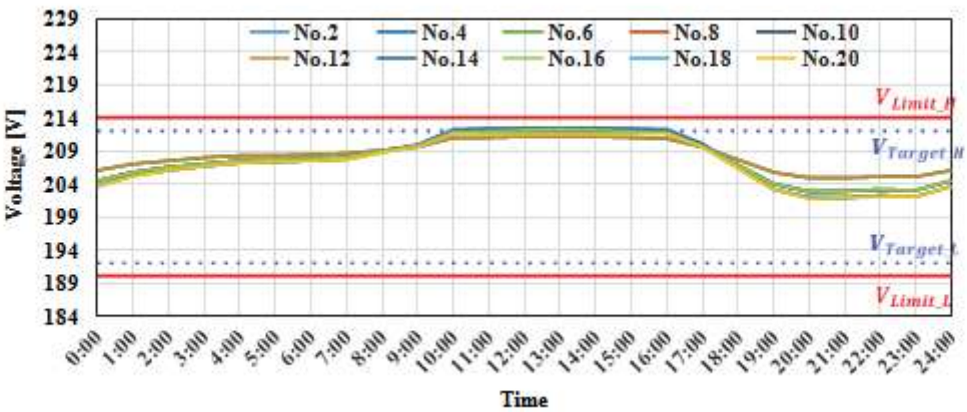
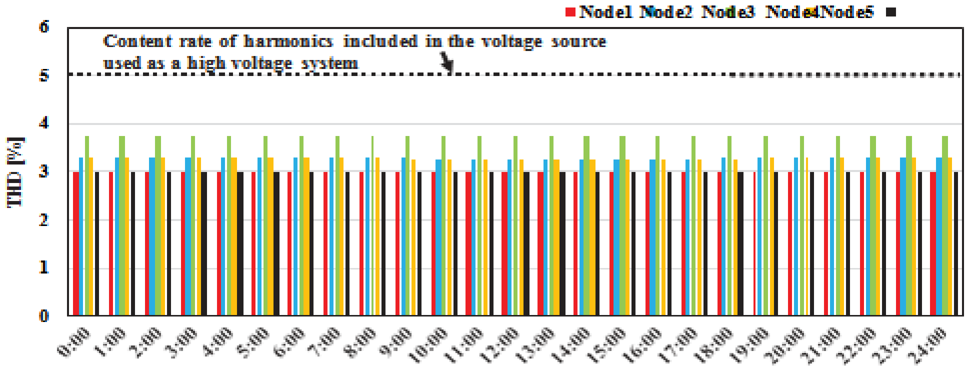


Figure 14. Consumer voltages with proposed control.



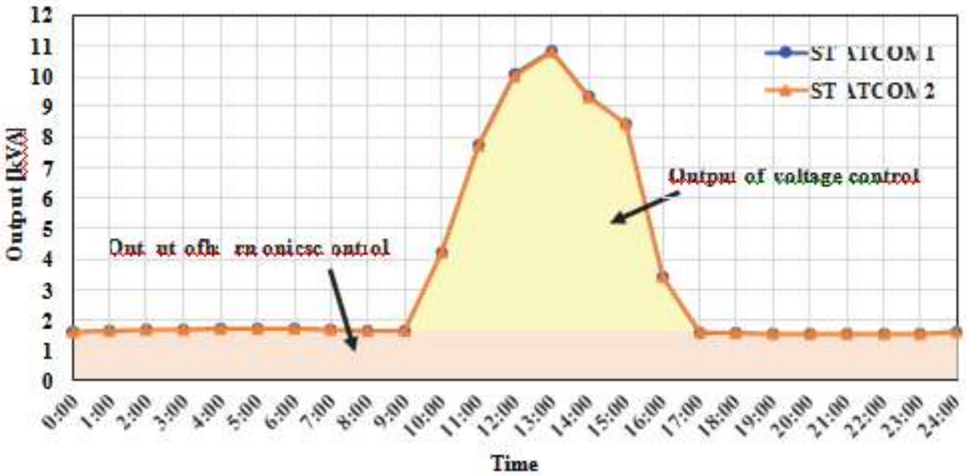


Figure16.OutputofSTATCOMswithproposedcontrol.(a)Interconnectionpointvoltage(node1voltage).(b)Outputcurrent.(c) Outputcurrentfromvoltagecontrolunit.(d)Outputcurrentfromharmonicscontrolunit.

$i_{STAT}{}^{m}$ ¼ $i_Q{}^{m}$þ$i_h{}^{m}$ (10)

IV. Numerical Calculation Example

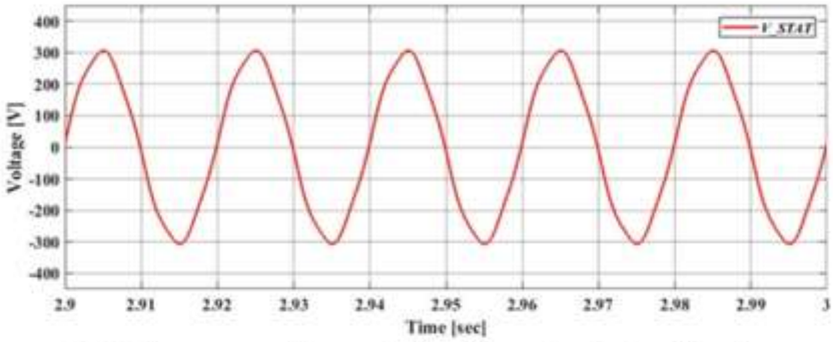
In order to verify the validity of the proposed method, the numerical calculations are carried out by using an analytical model of distribution system under wide- spread of PVs.

Analyticalmodelandsimulationcondition

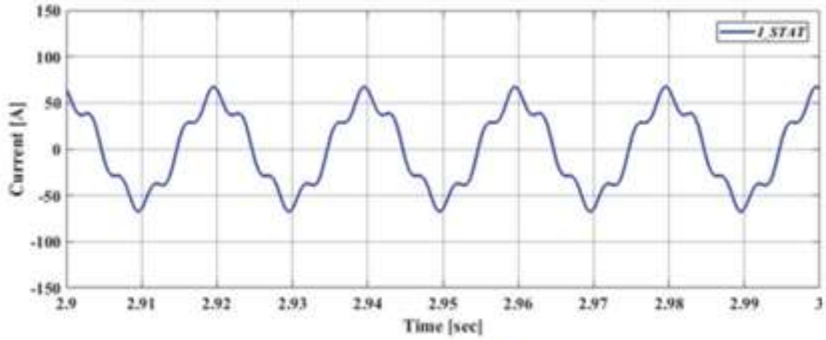
Theanalyticalmodelofthedistributionsystemisshown in Figure 5. In this figure, the high voltage system (6.6 kV-50 Hz distribution system) is simulated with a voltage source including the fifth harmonic voltage of 5%. In this study, the analysis target is a lowvoltage system supposed as a single-phase three-wire system. The simulation condition is shown in Table 1.

Thesupposedlowvoltagesystemisspreadtoleftand right from the pole transformer. STATCOMs are installed at Node1 and Node5, ends of the low voltage system. The target value of THD is set to 3% since 6.6 kV distribution system needs to be kept the voltage THD under 5% and the voltage distortion of each order harmonic under 3% as the level of harmonic environmental target in Japan[10].

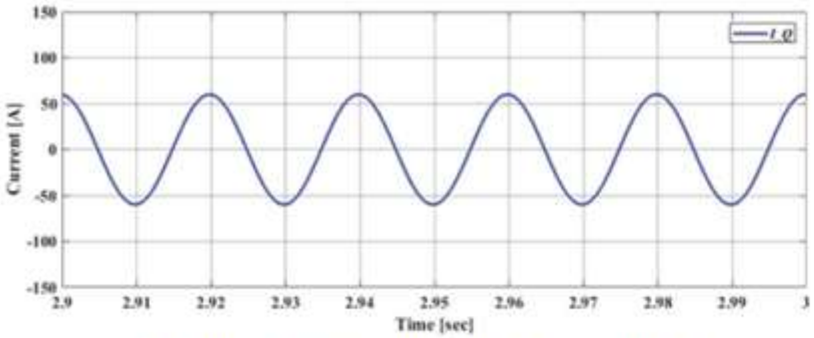
The total number of residential loads (consumers) are 20 and four of them are connected at each node. Moreover, most PVs are interconnected to end sides of the distribution system assuming the voltage deviation from the proper range. The consumers installed PVs are No.1, No.2, No.3, No.5, No.6, No.13, No.14,No.15, No.17, and No.18, it is 50% of the consumers.The load curve and the output of PV used for the numerical calculation are shown in Figure 6.



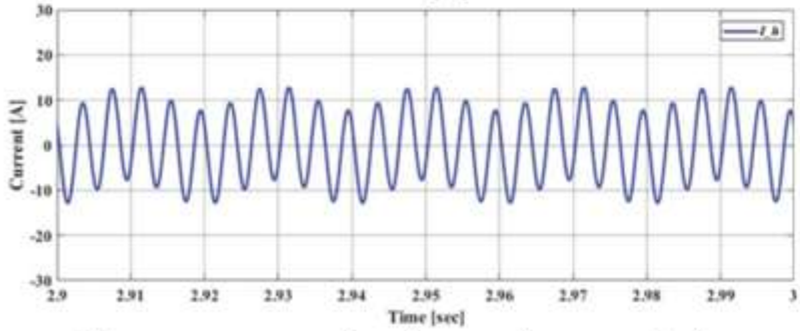
(a) Interconnection point voltage (node1voltage)



(b) Output current



(c) Output current from voltage controlunit



(d) Output current from harmonics controlunit

Figure 17. Waveforms of STATCOM1 at 13:00 with proposed control.

Simulation results

Figures 7–9 show simulation results withoutSTATCOM control. Figure 7 shows consumer voltages and the vol- tages deviate the upper limit of proper range in the day- timebytheinfluenceof PVs.Figure8showsthe THDof eachnodevoltage.InFigure8,thevoltageTHDiskeptto about 5% inallnodesbya voltages ourceusedas the high voltage system. However, in the daytime, voltage THDs areunder5%.Itisthoughttobecausedbytheincreaseof fundamental voltage by the influence of PVs. Moreover, Figure9showsthewaveformsofSTATCOM1at13:00.It can also be confirmed from Figure 9(a) that interconnec- tion point voltage (node1 voltage) deviates the upper limitofproperrangeandthewaveformitselfisdistorted. Atthistime,theoutputcurrentofSTATCOMsiszeroas shown in Figure 9(b), since STATCOMs are not operated.

Figures 10–13 show simulation results with con-ventional STATCOM control. Conventional control means only voltage control by reactive power control of STATCOM. Figure 10 shows consumer voltages and they are controlled within the proper range. However, the THD of each node voltage is still kept to about 5% as shown in Figure 11. Figure 12 shows the output of STATCOMs. As shown in Figure 12, STATCOMs are operated in the daytime depending on the amount of voltage deviation from the target range. Additionally, the value of each STATCOM output is almost the same, since the control amount is shared between each STATCOM to reduce the total capacity of itself. The maximum output is about 9.1 kVA. Moreover, Figure 13 shows the waveforms of STATCOM1 at 13:00. Compared with Figure 9(a), the peak value of interconnection point voltage (node1 voltage) is decreasing (Figure13(a)). It is thought to be caused by the reactive power control of STATCOM and the reactive output currentisshowninFigure13(b).

Figures 14–17 show simulation results withproposed STATCOMcontrol which isincluding the filteringfunc- tion. Figure 14 shows consumer voltages and they are controlled within the proper range. Additionally, the THDofeachnodevoltageisalsocontrolledanddecreas- ingto about 3% (Figure15). The THD of node3 voltageis larger than 3% and the largest value in all nodes. It is thought to be due to that node3 is located farthest from interconnection points of STATCOMs (node1 and node5). However, it is thought to be enough eff ect, since there is no rule about the voltage THD inlow

voltage system in Japan. The broken line in Figure 15means the content rate of harmonics included in the voltage source used as a high voltage system and the environmental target value of harmonics in a Japanese high voltage system. Figure 16 shows the outputs of STATCOMs. As shown in Figure 16, STATCOMs are operated throughout the day. The average output for harmonics control is about 1.7 kVA and the maximum output for voltage control is about 9.1 kVA. Therefore, the maximum total output of STATCOM is about 10.8 kVA. Moreover, Figure 17 shows the waveforms of STATCOM1 at 13:00. The waveform of interconnection point voltage (node1 voltage) is getting close to a sinusoidal wave with no distortion (Figure 17(a)). At this time, the output current of STATCOM is shown in Figure17(b).Itisatotalvalueofoutputcurrentsfromthe voltage control unit (Figure 17(c)) and theharmonics control unit (Figure 17(d)). It can also be confirmed from Figure 17 that STATCOM is compensating both the reactive power and harmonics voltage at the inter- connection point.

V. Conclusion

In this paper, the authors proposed the method of improvement of power quality by STATCOMs for low voltage system added the function of harmonic suppres- sion. In the proposed method, the STATCOMs are operated as the filtering function even when there is novoltagedeviationinlowvoltagesystemandcompen- sate both the reactive power and harmonic voltage atthe interconnection point throughout the day. In order to verify the validity of the proposed method, the numer- ical calculations were carried out by using an analytical model of distribution system under widespread of PVs. Simulation results showed the improvement eff ect of power quality on both sides of voltage deviation and harmonics.

In the future, it is necessary to investigate the coop- erative control method with another voltage devices. Moreover, the authors will develop a STATCOM for low voltage system and verify the usefulness of the proposed method using the experiment facilities.

Disclosure statement
No potential conflict of interest was reported by the authors.

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