International Conference on Renewable Energies and Power Quality (ICREPQ'19)
Tenerife (Spain), 10th to 12th April, 2019
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.17, July 2019

Use of FACTS for Improving Voltage Stability in Mining Applications

J. L. Olabarrieta Rubio[1], P. Eguia Lopez[2], E. Torres Iglesias[2], A. Etxegarai Madina[2]

[1] ABB Ring Motors Spain
Barrio Galindo S/N, 48510 Trapagaran (Spain)
Phone/Fax number:+0034 658 717090, e-mail: **jose-luis.olabarrieta@es.abb.com**

[2] Department of Electrical Engineering, Faculty of Engineering of Bilbao, Universidad del País Vasco UPV/EHU
Plaza Ingeniero Torres Quevedo 1, 48013 Bilbao (Spain)
Phone/Fax number:+0034 946 017332, e-mail: **pablo.eguia@ehu.eus**

Abstract. FACTS systems provide a well proven solution for actual different power system problems. FACTS devices can be effectively used for reactive power support, enhance controllability, improve stability and increase power transfer capability of AC transmission systems. This paper analyses the utilisation of FACTS systems in the expansion project of a mine, as an environmental solution for optimizing existing exploitations instead of opening new mines.

Key words

FACTS, mine, GMD, synchronous motor, STATCOM, SVC.

1. Introduction

Natural resources are running out, being minerals one of the most drained natural resource. In 2005 mining installations extracted 10 kg of copper from each ton of mineral, while in 2016 this amount decreased to 6 kg.

This reduction in mineral purity together with the increasing demand of minerals (China consumes 30% of the world production) is challenging for the mining industry, redirecting this sector to mining technologies more intelligent, sustainable, efficient and safer.

Due to the increasing consumption of copper, in the next 25 years we will have to produce the same quantity of copper than in the last 100 years. The necessity to make deeper prospections due to the drop in mineral purity doubles the time needed to obtain the same production, and this translates to an increase in costs (production costs have increased 120% in the last 10 years)[1].

Mine owners are suffering a growing competitiveness and the solution goes through two basic steps: optimization of existing installations and technologies, and creation of new mining installations.

The opening and exploitation of a new mine is a complex undertaking. Environmental impact and engineering assessments have to be carried out, and a bewildering array of permissions, licenses, agreements, and authorization (construction, explosives, etc.) need to be obtained.

As a result, mine owners often choose to increase the productivity of existing mines by expansion, instead of opening new ones.

Since the late 70´s FACTS systems appeared as an initiative of Electric Power Research Institute (EPRI) for providing reactive compensation using power electronics.

So far, FACTS are a reliable solution when power flow control, voltage regulation, enhancement of transient stability or mitigation of system oscillations are needed [2]. In the mining industry, these systems could be a good solution when an increase of productivity is needed.

Due to all this, FACTS systems solution can be applied to mine expansion projects, increasing system performance, especially:

- Transient stability enhancement
- Voltage stability enhancement
- Economy

This paper explores the use of a FACTS solution applied to a mine expansion project (an existing mine with two new mills). Voltage and transient stability are analysed, before and after the new mills placement.

The paper is organized in 5 sections, including this introduction. Section 2 analyses the problems for expansion of existing mines. Section 3 reviews the application of FACTS in mining. Section 4 details the case study, the analysis and the results. Finally, section 5 resumes the main conclusions.

2. Expansion of existing mine projects

In the mining industry, several different types of mill are used to grind ore into smaller pieces for further processing:

- Ball mills consist of a rotating horizontal hollow cylinder, with an abrasion-resistant interior. The grinding is performed by free-moving stone, metal or rubber balls that are lifted to a certain height by natural adhesion to the inside of the cylinder.
- Autogenous (AG) mills are similar but have internal lifting plates and use large ore particles as the grinding media.
- If the ore is too hard or abrasive, steel balls may be added – the mill is then called a semi-autogenous (SAG) mill.

AG and SAG mills can be used as a one-stage grinder but are often used as the first stage in a two or multiple-stage grinding process, an important stage in mineral processing, where the second stage is carried out by the ball mill. These mills are driven by large gearless motor drives (GMD).

A. Gearless motor drives

The gearless mill drive eliminates all mechanical components of a conventional mill drive system, such as ring-gear, pinion, gearbox, coupling, motor shaft and motor bearings. By mounting the rotor poles directly onto the mill, the mill itself becomes the rotor of the gearless motor.

These grinding mills are responsible for more than 60% of the electric power consumed in modern copper concentrator plants. When adding new mills to an existing mine infrastructure, a paramount consideration is the robustness of the electrical grid - ie, its ability to supply steady voltage and frequency irrespective of load and grid disturbances [3].

Moreover, mines are often located in remote areas and at the end of long transmission lines, which makes the power supply even weaker, and more vulnerable and unpredictable. In these weak grids, the active and reactive power consumption of GMDs, generators, lines and transformers lead to voltage drops and poor power quality. In such situations, voltage stability is a critical consideration in improving power security and reliability.

B. Synchronous motors

Motors used in GMD drives are synchronous motors, with an apparent power between 20 and 30 MVA. These are low-speed units, operating in 9-12 r/min speed range and have an internal diameter between 10 and 15 meters. With 60-72 poles, these motors are fed by cicloconverters, that convert AC to a lower frequency AC with no intermediate DC link.

3. Application of FACTS in mining

Most suitable FACTS systems applied to mining electrical systems are shunt-connected FACTS controllers. These devices are capable of generating or absorbing reactive power, varying output and controlling specific and desired parameters of the power system [4].

Among shunt-connected FACTS, we can highlight SVC (Static Var Compensator) and STATCOM (Static Synchronous Compensator).

Both SVC and STATCOM work as controlled reactive-power sources. Voltage stability is dependent on the reactive power, if we can improve the reactive power to meet the demand, we will improve the voltage profile of the system. SVC and STATCOM provide the desired reactive-power generation or absorption entirely by means of electronic switching of reactors and capacitors (SVC), or by electronic processing of the voltage and current waveforms in a voltage-source converter (STATCOM).

STATCOM device has some advantages when compared with SVC, e.g., current injection independent of system voltage, faster control and less space requirement.

4. Case study

The case study consists of a mine electric system with GMDs in Chile. The plant has two voltage levels, 69 kV and 23 kV. The original configuration of the mine consists of three lines of crushing with three GMDs: one 20 MVA SAG and two 14.2 MVA BALL. The mine electrical system is connected through a 220 kV substation to the Chilean SING system. The power system in Chile is composed by 4 subsystems: SING, SIC, Aysen and Magallanes. The model that represents the SING subsystem can be downloaded from the Chilean National Electric Coordinator web page [5].

The study has been performed using the power system simulation software DIGSILENT Powerfactory. Figure 1 shows the model of the mine electrical system. This model has been connected to the SING model at the 220 kV busbar of the interconnection substation.

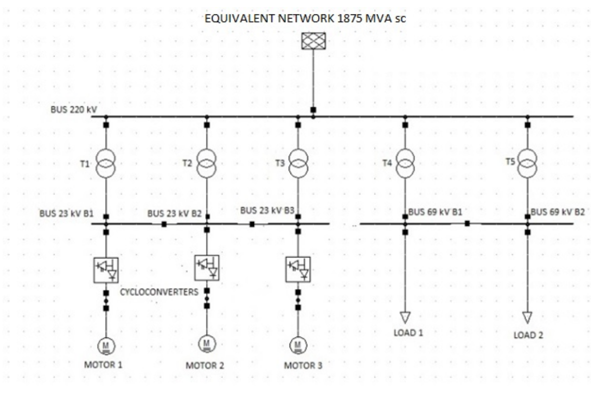

Fig. 1. 23 kV mine electrical system

Data of the main equipment considered in the model is included in Tables I and II. Synchronous motors are connected to the bus by means of cicloconverters (not included in this simulation).

Table I. Transformers and load characteristics

NAME	POWER [MVA]	VOLTAGE [kV]	Zcc (%)
T1, T2,T3	85	220/23	15
T4, T5	50	220/69	12.5
LOAD1, LOAD2	18	69	

Table II. Synchronous motors characteristics

NAME	M1	M2,M3
Power [MVA]	20	14.2
Speed [rpm]	9.3	11.5
Moment of Inertia [kgm2]	33846754	26938000
Synchronous reactance d-axis non-saturated Xd [p.u]	0.885	0.933
Transient reactance d-axis non-saturated Xd´ [p.u]	0.34	0.363
Synchronous reactance q-axis non-saturated Xq [p.u]	0.701	0.768
Subtransient reactance q-axis non-saturated Xq´´ [p.u]	0.698	0.765
Damper circuit time constant in d-axis non-saturated Td	0.029	0.03
Damper circuit time constant in q-axis non-saturated Tq	0.028	0.03
Transient short-circuit-time constant d-axis non-saturated Td´	3.195	3.426
Subtransient short-circuit-time constant q-axis non-saturated Tq´´	0.028	0.029

A. Description of the problem.

After several years of exploitation, the mine owners have decided to increase the capacity. A project exists to expand the mine with two new motors, a 20 MVA SAG motor and a 14.2 MVA BALL motor. This paper analyses the effect of adding these motors to the electrical system of the mine.

In steady state operation, the addition of the new load produces an increase in the voltage drop as well as higher risk of voltage collapse during overloads. In these conditions, the only way to save the system from voltage collapse is to reduce the reactive power load or to add additional reactive power compensation by introducing new sources of reactive power, i.e., shunt capacitors and/or FACTS controllers at the appropriate location. Introducing FACTS devices is the most effective way to improve the voltage profile and voltage stability margin of the system [6].

During transient events, the operation of the mine is also affected by the addition of the new motors. As an example, Figure 2 shows the active and reactive power demand of the 14.2 MVA BALL motor during start-up.

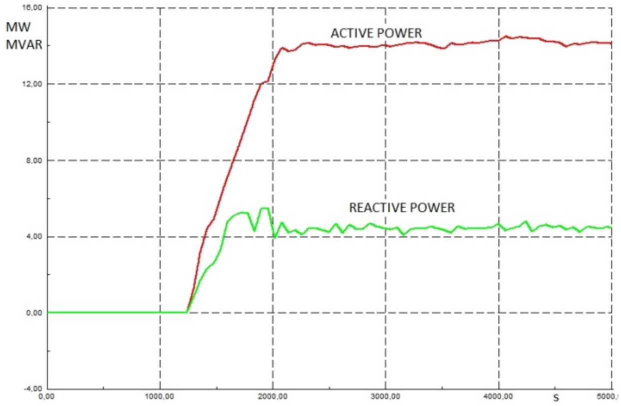

Fig. 2. Active and reactive power consumed by the start-up of the 14.2 MVA BALL motor.

The voltage at the 23 kV bus is affected by the new motors causing an additional 2% voltage drop.

Fig. 3. Voltage level (pu) in 23 kV bus.

B. Placement and sizing of shunt FACTS controller.

Location of shunt compensation devices is important for the enhancement of voltage stability in electrical power systems [7]. Various indicators are proposed to study the voltage stability margin of the system. The indices calculated for stability analysis can be referred to a bus or line determining the most unstable bus or line of a system [8]. In this paper PV curves has been chosen for calculating the critical bus and line of the system. Placing FACTS controllers at the proper place increases the load ability margin and hence the stability of the system [9]. The best location for reactive power compensation for improving steady state voltage stability margin is the weakest bus in the system [10, 11, 12].

The variation of steady-state bus voltage values with the loading factor has been obtained for the different buses (220 kV, 69 kV and 23 kV) of the mine electrical system. The results show that 23 kV bus is the most insecure bus in the system, in terms of voltage stability, as shown in Figure 4.

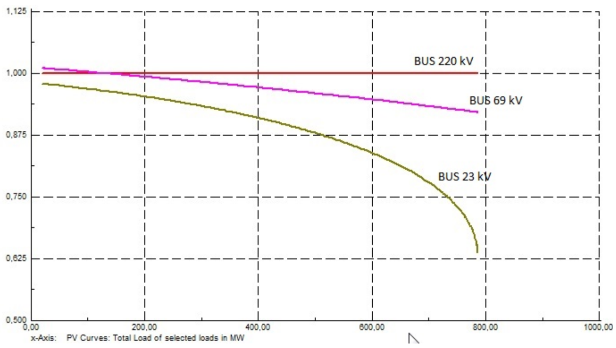

Fig. 4. PV curves of the system

Once the location of the FACTS has been selected, the rating must be defined. The sizing of a reactive compensation equipment depends on the short-circuit power at the Point Of Interconnection (POI) and the voltage drop to compensate. The required capacity of the FACT can be described with equation (1):

$$\Delta U\,(\%) = \frac{Q}{Scc} * 100 \qquad (1)$$

Where ΔU(%) is the variation of the POI voltage in percentage, with reference to nominal voltage, Q is the reactive power of the FACTS and Scc is the short-circuit power at the POI.

For the case study, with 1000 MVA short-circuit power at the 23 kV bus, a 20 MVAR FACTS will be able to compensate 2 percent of the nominal voltage.

C. Type of FACTS

It has been verified in Figure 4 that the expansion of the existing mine with 2 additional motors affects the voltage stability of the mine electrical system. In order to improve it, the use of a FACTS shunt device is analysed. Two solutions have been studied, the use of a 20 MVAr STATCOM and the use of a 20 MVAr SVC.

STATCOM

The use of a 20 MVAr STATCOM connected to the 23 kV busbar improves the voltage profile after the motors start-up, as the STATCOM detects and instantly compensates voltage fluctuations, injecting reactive power to the system [13]. Cost of STATCOM is about 80 US dollar/kVAr [14, 15].

A model of the STATCOM has been implemented to test the improvement in voltage during steady state and transient regime of the mine installation. The model is a current injection model. To exchange the reactive power between the ac system and STATCOM, the STATCOM current is always kept in quadrature to the bus voltage. The model includes a Power Oscillation Damping (POD) controller for damping oscillations during transient conditions. Figure 5 shows the main control loop of the STATCOM dynamic model.

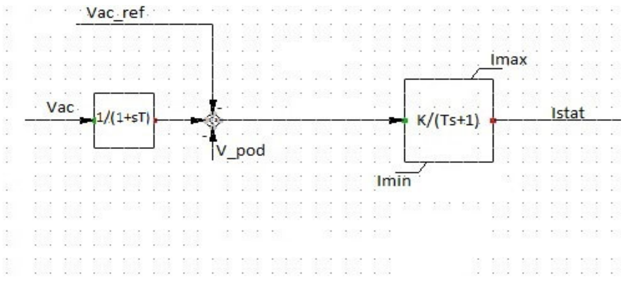

Fig. 5. STATCOM main control loop

In Figure 5, Vac is the control bus voltage, Vac_ref is the reference voltage of the regulator, V_pod is the normalised output voltage of the POD , K is the controller gain, T is the current controller time constant, Imax is the maximum current in capacitive mode, Imin is the maximum current in inductive mode and Istat is the STATCOM current.

Table III. STATCOM controller values

K[pu]	10
T[s.]	0,09
Imax[pu]	1
Imin[pu]	-1

SVC

Similarly, a model of a SVC has been implemented. The SVC is modelled as a +/- 20 MVAr voltage controlled shunt susceptance (Bsvc), being similar to a synchronous compensator, except that it has no mechanical inertia and the speed of response is much faster. Cost of SVC is about 40 US dollar/kVAr [14, 16].

Figure 6 shows the main control loop of the SVC, which is similar to the STATCOM model.

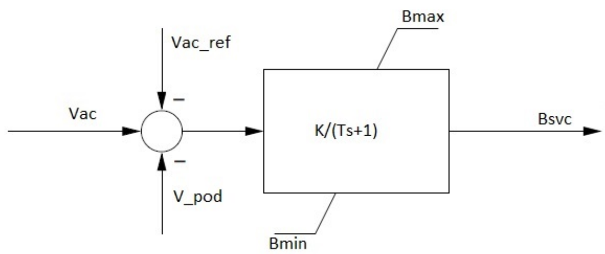

Fig. 6. Control of SVC

In Figure 6, Bsvc is the SVC susceptance, Bmax the maximum susceptance in capacitive mode and Bmin the maximum susceptance in inductive mode.

Table IV. SVC controller values

K[pu]	100
T[s.]	0,01
Bmax[pu]	0,94
Bmin[pu]	-0,94

POD

Due to the low speed and large inertia of the SAG and BALL motors, sustained and poorly damped oscillations in the voltage appear after short-circuit faults. In order to improve the damping, a POD has been implemented in the STATCOM and SVC models. The POD controller outputs a complementary voltage regulation signal [17] in the main control loop and it consists of a gain (first block), with a washout filter (second block) connected in cascade with linear lead-lag filters (third and fourth blocks). Figure 7 shows the POD control loop and Table II list the constant values used in the STATCOM and SVC models.

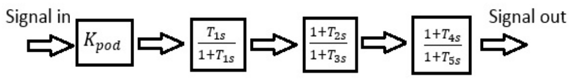

Fig. 7. POD regulator structure.

Table V. POD regulator values.

	STATCOM with POD	SVC with POD
Kpod	2	100
T1 [s.]	0,8	0,8
T2 [s.]	1,5	1,5
T3 [s.]	0,8	0,8
T4 [s.]	1,5	1,5
T5 [s.]	0,5	0,01

D. SVC and STATCOM response during motor start-up

The same motor start-up shown in Figures 2 and 3 has been repeated with the STATCOM and the SVC connected to the 23 kV bus. Figure 8 shows the results. In both cases, the reactive power provided by the FACTS is similar.

Fig. 8. STATCOM and SVC injected reactive power (MVAr) during start-up of the 14 MVA SAG and 14.2 MVA BALL motor

E. Transient stability study

To analyse the transient stability of the system after a short circuit, a 3 phase short circuit is applied in the weakest bus, this is 23 kV bus. The duration of the short circuit is fixed by the national standard, which fixes the duration to one second [18].

As stated before, due to the high inertia of the GMD motors, the voltage suffers large poorly damped oscillations during tens of seconds, as can be seen in Figure 9.

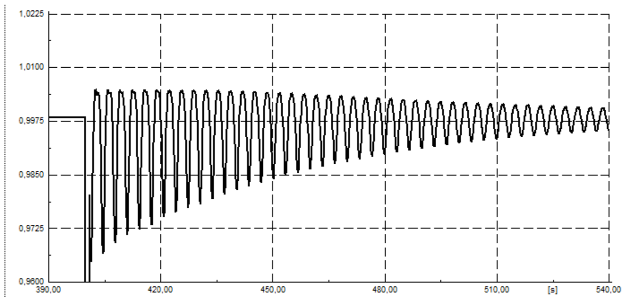

Fig. 9. 23 kV bus voltage for a 3 phase short circuit

The same event has been simulated with the STATCOM and the SVC with the POD controller. The desired effect is to compensate the reduction in voltage of the new motors and, at the same time, to reduce post fault oscillations, increasing the transient stability margin. The voltage at the 23 kV for each FACTS solution be seen in Fig 10, superimposed to the situation when there is no FACTS installed.

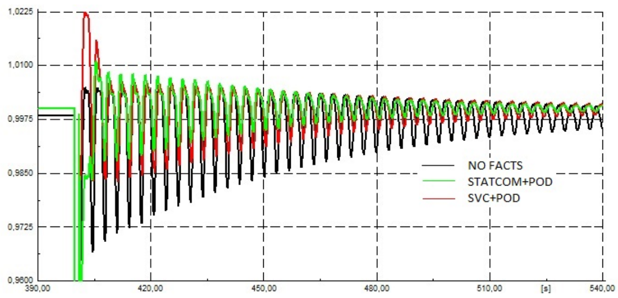

Fig. 10. 23 kV bus voltage for a 3-phase short circuit with FACTS

Both STATCOM and POD improve the voltage before the fault and reduces the post fault oscillations, but the STATCOM with the POD offers a better response, with lower voltage variation and faster oscillation damping. This can be clearly seen in the zoomed image in Figure 11.

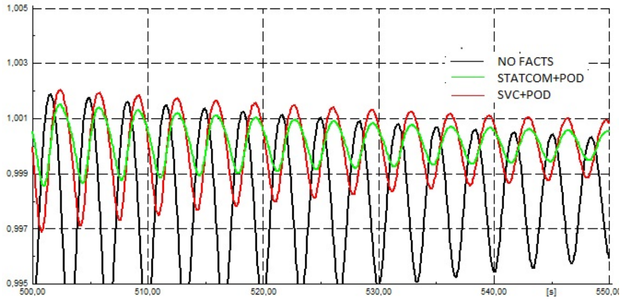

Fig. 11. Detail of Figure 10

5. Conclusions

The main findings and conclusions of the paper can be summarized as follows:

- FACTS devices are a good solution for mine expansion projects, providing adequate reactive power at the point of injection maintaining the voltage stability of the mine electrical system.
- Correct placement (i.e. with PV curves) and sizing of the FACTS solution are two of the main variables to focus when designing these elements.
- With the addition of a POD the enhancement of transient stability and voltage oscillations are also achieved.
- The proposed reactive power controllers can effectively damp the torsional oscillations and enhance the transient stability of the studied system during a 3 phase short circuit fault.
- The results show that STATCOM with POD is slightly more effective in damping oscillation when compared with SVC with POD.

Acknowledgement

The authors thank the support from the Basque Government (GISEL research group IT1083-16), as well as from the University of the Basque Country UPV/EHU (research group funding PPG17/23).

References

[1] Ministerio de mineria-Gobierno de Chile, "Mineria en numeros" http://www.minmineria.gob.cl/con-mineria-se-aprende/mineria-en-numeros/

[2] Yong Hua Song, Allan T. Johns, "Flexible AC Transmission Systems (FACTS)" 1999.

[3] ABB OPEN PIT MINING: https://new.abb.com/mining/open-pit-mining

[4] R. Mohan Mathur and Rajiv K. Varma, "Thyristor-based FACTS controllers for electrical Transmission systems"," IEEE PRESS.

[5] Coordinador electrico nacional Chileno. http://cdec2.cdec-sing.cl/pls/portal/cdec.pck_

[6] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, New York: IEEE Press, 2000

[7] A.R. Phadke, S. K. Bansal and K. R. Niazi, "A Comparison of Voltage Stability Indices for Placing Shunt FACTS Controllers," 2008 First International Conference on Emerging Trends in Engineering and Technology, Nagpur, Maharashtra, 2008, pp. 939-944

[8] Claudia Reis, Antonnio Andrade, F.P Maciel," Line Stability Indices for Voltage Collapse Prediction," IEEE conference, Lisbon ,Purtugal,March 18-20, 2009

[9] B.Gupta and P. R. Sharma, "Optimal placement of FACTS devices for voltage stability using line indicators," 2012 IEEE Fifth Power India Conference, Murthal, 2012, pp. 1-5.

[10] A. Sode-Yome, N. Mithulananthan and Y. Lee Kwang, "A Comprehensive Comparison of FACTS Devices for Enhancing Static Voltage Stability", IEEE Power Engineering Society General Meeting, 2007

[11] C. A. Canizares, A. C. Z. de Souza, and V. H. Quintana, "Comparison of performance indices for detection of proximity of voltage collapse", IEEE Trans. Power Syst., vol.11, pp. 1441-1450, Aug. 1996.

[12] A. Sode-Yome and N. Mithulananthan, "Comparison of shunt capacitor, SVC and STATCOM in static voltage stability margin enhancement", International Journal of Electrical Engineering Education, UMIST, Vol. 41, No. 3, pp. 158-171, July 2004.

[13] J. L. Olabarrieta, P. Eguia, "FACTS brings power stability to mining equipment", ABB review, 03/2018, pp 20-25

[14] B. Ramanathan, D. Elizondo, J. Enslin and L. Zhang, "Cost Effective FACTS Solution for Transmission Enhancement and its Economic Assessment," 2006 IEEE/PES Transmission & Distribution Conference and Exposition: Latin America, Caracas, 2006, pp. 1-6.

[15] R. Visakhan, R. Rahul, K. R. Hridya and A. A. Kurian, "Analysis of power oscillation damping capability of STATCOM-POD and optimal placement of PMUs in IEEE-14 bus system," 2015 International Conference on Power, Instrumentation, Control and Computing (PICC), Thrissur, 2015, pp. 1-7

[16] CIGRE. Static Var Compensators. Prepared by Working Group 38-01 Task Force No.2 on SVC. Paris 1986.

[17] S. Asawa and S. Al-Attiyah, "Impact of FACTS device in electrical power system," 2016 International Conference on Electrical, Electronics, and Optimization Techniques (ICEEOT), Chennai, 2016, pp. 2488-2495

[18] Gobierno de Chile-Comision Nacional de Energia, Norma Tecnica de Seguridad y Calidad del Servicio. May 2018