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Article

Effects of Voltage Dips on Robotic Grasping

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Abstract: This paper addresses the effects of electric power quality on robotics operation. A general overview is reported to highlight the main characteristics of electric power quality and their effects on a powered system by considering an end-users viewpoint. Then, authors outline the influence of voltage dip effects by focusing at robotic grasping applications. A specific case of study is reported as referring to LARM Hand IV, a three-fingers robotic hand, which has been designed and built at LARM in Cassino. A dedicated test rig has been settled up for generating predefined voltage dips. Experimental tests are carried out for evaluating the effects of different types of voltage dips on the grasping of objects.

Keywords: Robotic Hands, Grasping, Electric Power Quality, Voltage Dips effects

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1. Introduction

Nowadays, electronic equipment and computing devices are used in most types of industrial machines and robotics devices. They are a key for the successful implementation of most industrial processes. But, the wider use of electronics makes this equipment more vulnerable to the disturbances in terms of power quality (PQ). PQ is related to several disturbances that include among others momentary interruptions, voltage dips or sags, swells, transients, harmonic distortion, electrical noise, and flickering lights, [1]. The electrical power grid is designed for delivering power reliably and aiming at maximizing the power availability to the customers. However, the PQ disturbances are not always taken into consideration while they can significantly affect the industrial production as well as permanently damage expansive equipment, costing industrial customers millions of dollars, [2]. In order to minimize these costs, it is critical for industrial customers to understand how PQ can affect the operation of their systems and how it is possible to mitigate the effects of PQ disturbances, [1-3].

The international framework of the actual standards on PQ is based on the norms of the IEC (International Electro-technical Commission), which is accepted as a worldwide reference. Moreover, national or supranational committees give further indication on the maximum limits to be imposed on PQ disturbances. For example, the CENELEC (European Committee for Electrotechnical Standardization) is the European reference while CEI (Comitato Elettrotecnico Italiano), is the Italian national reference for adopting IEC and CENELEC standards. The above-mentioned bodies have released the norm EN 50160 that defines the European and Italian standards for the PQ in terms of voltage dips and other voltage disturbances. Similarly, the norms EN 61000-4-11 and EN 61000-4-34 are adopted worldwide, [4-7].

The PQ is gaining significance also in robotics and specifically in applications of service robotics with co . The voltage dips, also defined with the equivalent term voltage sags, are recognized as one

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of the most severe disturbances which can affect the operation of industrial devices. The detrimental effects of voltage dips can result both in the tripping of the protective devices with the equipment shut down and in the malfunction of the device. This latter consists in a sort of failure that determines a functionality far from a normal or satisfactory manner. Both these typologies of effects have significant economic impact on the factory. These costs depend on many factors that are linked to the type of manufacturing activity and to the extent of the affected area, [3].

Among other industrial devices, the robots certainly suffer for the presence of the voltage dips in the supply voltage. This is particularly critical in the case of collaborative robots which are penetrating even more in several applications also thanks to the [8]. This recent ISO norm, in fact, establishes a novel regulatory framework allowing a wide spread of collaborative robots the in industrial and civil environments. The close interaction among robots and humans makes safety one of the most significant aspects of robot design and operation. Clearly, the effects of the voltage dips in the supply voltage can significantly influence the robot performance as well as can generate safety issues potentially critical such as missing operations or unpredictable robot behaviours.

The case of robot grasping is quite significant, since the performance of the end effector is considered to be the most important contribution for achieving a successful manipulation of an object. Several researchers have been addressing the design of grasping devices with solutions ranging from simple end-effectors (suction cups, electromagnetic devices), two finger grippers for handling specific objects up to complex multi-purpose robotic hands, [9-11]. It appears very significant to investigate the effects of power quality on a robot grasping, since a grasping failure implies a failure of the whole robotic manipulation procedure. Moreover, this can have strong safety implications especially in collaborative robotics tasks, as mentioned in [8].

This paper will address the effects of the voltage dips on the performance of the robotic grasping. A specific case of study is reported as referring to LARM Hand IV, a three-fingers robotic hand, which has been designed and built at LARM at the University of Cassino, [12-15]. A dedicated test rig has been designed and settled up for generating predefined voltage dips to experimentally investigate their effect on the grasping of objects with different sizes. Experimental tests are carefully analysed and discussed to demonstrate the influence of the voltage dips on the grasping performance as well as to propose some mitigation actions to avoid safety implications during the grasping.

2. Main Characteristics of the Voltage Dips

The term PQ embraces a wide set of disturbances that can affect the voltage and/or the current [3]. The disturbances are categorized in two groups: the variations and the events [4]. Each group represents different types of phenomena and different ways of treating the disturbances [5-6]. The variations and the events are due to the interaction between the power supply and the devices installed at the customers' premises.

Variations are minor variations from the ideal value of voltage or current that show relatively slow changes in value. The level of variations can be measured continuously and at predefined instants of time. Examples of variations are the voltage amplitude variations and the waveform distortion. Events are larger deviations from the ideal value that occur suddenly. Events cannot be measured continuously because they only occur occasionally. A trigger condition is needed to measure events. In the group of the events affecting the supply voltage, the voltage dips are one of the most severe disturbance that can affect the industrial loads. Several devices are vulnerable to the voltage dips. The main detrimental effects of the voltage dips are the tripping of protected devices and the degradation of the performance of the equipment.

A voltage dip is defined as a sudden reduction of the supply voltage, below the 90% and above the 1% of the declared voltage, followed by a voltage recovery after a short period of time" [4]. Fig. 1 shows an example of a plot versus the time of a voltage affected by a dip. In Fig.1, the main characteristic quantities of a voltage dip are evidenced: the amplitude, indicated in Fig.1 with the symbol Vr, and the duration, indicated in Fig.1 with the symbol ◎t. The amplitude of a voltage dip is

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the minimum value of the RMS voltage during even; it is known also as the residual voltage. The duration of a voltage dips is the time elapsed when the voltage falls below the threshold value (90% of the rated value).

Further quantities can characterise a voltage dip like the number of involved phases, the phase angle jump, the symmetry of the voltage dips on the phases, and do on.

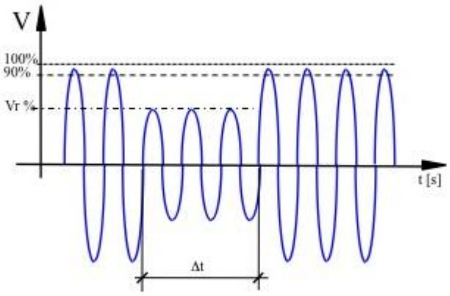

Figure 1. Example of voltage dip.

In the transmission and distribution systems, most of the voltage dips are originated by the short circuits; further causes are the start of a large motor, the insertion of a large transformer or of a high power load, as frequently can happen in the industrial systems. In the transmission and distribution systems, the dips are more frequently originated by short circuits in some nodes of the network. In the presence of a symmetrical solid short circuit in a specific node, two main phenomena happen. In the node where the short circuit occurs, the voltage is equal to zero, in the other nodes electrically close to it, the voltage is affected by the sudden reduction that represents a voltage dip. This phenomenon last until the protection device clears the short circuit.

The framework of the actual standards valid on the limits on the voltage dips is mainly referred to the IEC and to the CENELEC. In particular, the IEC 6100-4-11 [7] states the immunity test for the devices to define its operation class with reference to the EMC (Electro Magnetic Compatibility); two main classes are defined which are the Class II and the Class III. The main standard of the CENELEC is the EN50160 that indicated the voltage characteristics of the electricity supply by public distribution network. In particular, for the voltage dips, the standard proposes the table shown in Table 1 to classify them according to residual voltage and duration

Table 1. Classification of the voltage dips according to residual voltage and duration.[EN50160]

Residual Voltage u %	Duration t ms				
	$10 \leq t \leq 200$	$200 < t \leq 500$	$500 < t \leq 1\,000$	$1\,000 < t \leq 5\,000$	$5\,000 < t \leq 60\,000$
$90 > u \geq 80$	A1	A2	A3	A4	A5
$80 > u \geq 70$	B1	B2	B3	B4	B5
$70 > u \geq 40$	C1	C2	C3	C4	C5
$40 > u \geq 5$	D1	D2	D3	D4	D5
$5 > u$	X1	X2	X3	X4	X5

Table 1 refers to all the voltage dips that can be recorded in a node. It allows for immediately ascertaining the performance of the node in a considered period, typically at least of one year. Actually, the trends of future regulatory activities on the voltage dips are toward the limitation of the number of the voltage dips that can be present at any node of a system in a defined time period as the year. The limits could be expressed using a table similar to that in Table 1. In such a case, any

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number of the cell would express the boundary of the performance of the power supply that any customer should expect. Summarising, the most important characteristics of a voltage dip are the amplitude and the duration.

3. Main features of LARM Hand IV

Several designs have been developed as LARM Hand at LARM in Cassino, as detailed for example in [12-15]. The LARM Hand prototypes have three one-DOF human-like fingers. Their main features are low-cost and easy-operation. One of the most complex issues for achieving these results has been the design of a suitable driving mechanism that is embedded in the finger body and remains within the finger body also during its movement as shown in the scheme of Fig.2.

The LARM Hand IV, shown in Fig.3, is also equipped with three force sensors on each finger for measuring the grasping force on each phalanx while its operation is achieved by means of a low-cost PLC, which directly drives the three DC motors. A simple control logic is achieved by using a reference force threshold and by limiting the motor input current as it is directly linked with the motor output torque. It is worth noting that a firm grasp is achieved when all forces are in equilibrium. Therefore, the input torque has to change as function of several parameters including the external force acting on the object, and the position, size, shape of the grasped object.

In this paper, we investigate how voltage dips influence the grasping of an object while using LARM Hand IV.

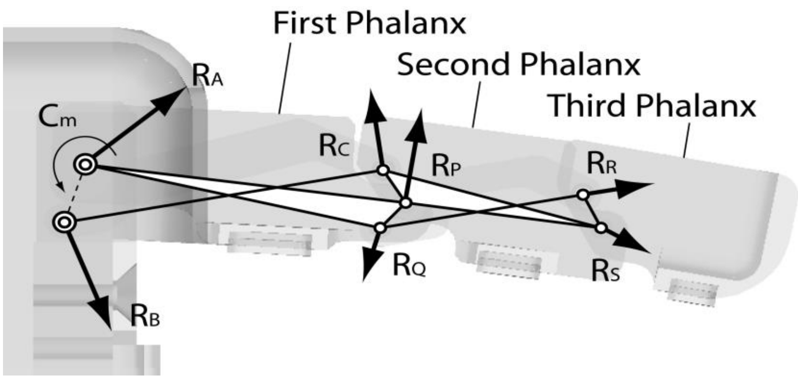

Figure 2. A CAD model of LARM hand with its transmission mechanism and reactions in joints.

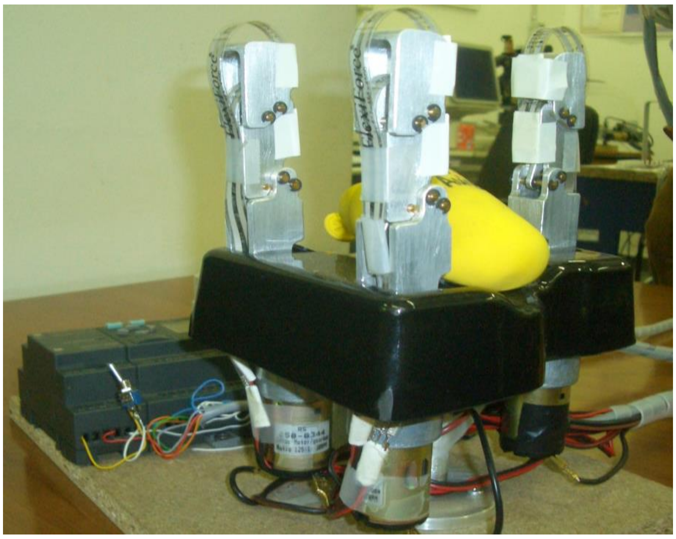

Figure 3. A prototype of LARM Hand IV.

4. Test rig set-up

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Experimental activities have been carried out to validate the effects of voltage dips by developing a dedicated test rig. The proposed test rig set up is outlined in Fig. 4.

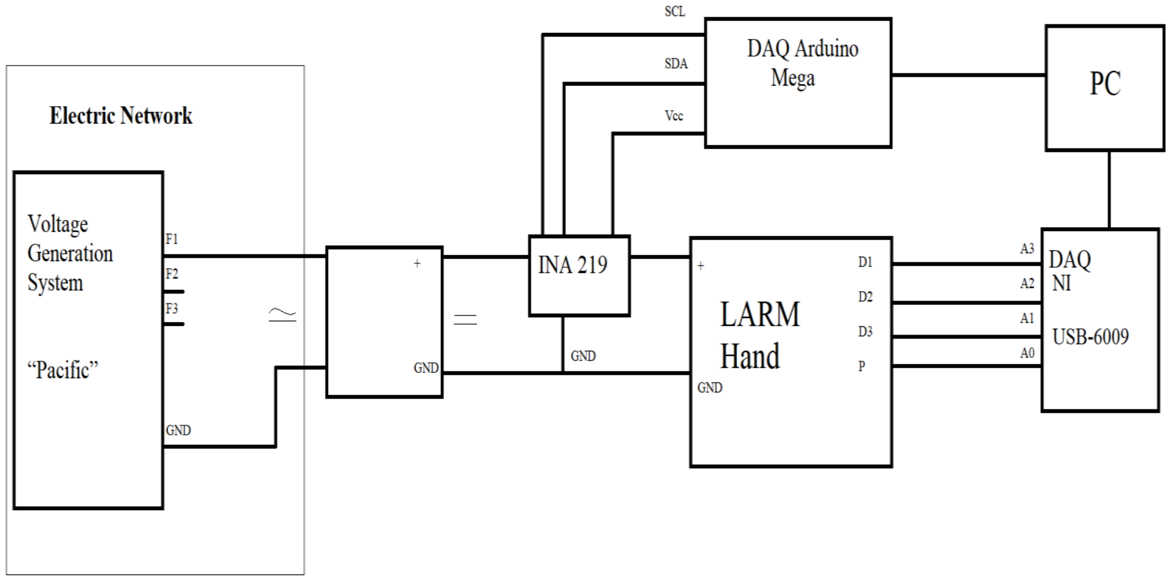

Figure 4. A scheme of the proposed test rig.

The main components of the proposed test rig are:

1- A Voltage Generation System by Pacific company;
2- A stabilized Power Supply model Elind 32dp32;
3- A current Sensor INA 219;
4- LARM hand IV prototype as in Figure 2;
5- An Arduino Mega board;
6- A National Instruments data acquisition board DAQ NI-6009 USB;
7- A PC or laptop with USB ports.

The Voltage Generation System is used to emulate the role of the electric network behaviour. In fact, it can generate any predefined waveform. The Voltage Generation System "Pacific", is connected to a dedicated PC via GPIB. Its operation is managed by using a dedicated software called UPC Manager. This device is used to generate pre-defined Voltage Dips. The Stabilized Power Supply that has been used is a high performance power supply with fast recovery time and low current ripple. A Texas Instruments current sensor INA 219 has been selected for measuring the power supply to the LARM Hand. This has been selected due to its low cost and easy operation in combination with a cheap Arduino Mega board. Furthermore the sensor resolution is suitable for the current absorbed by LARM Hand. A National Instruments DAQ NI-6009 USB has been used for collecting voltage outputs. This has been chosen for its convenient features in terms of costs, user-friendliness and performance for the data acquisition of the analog data outputs generated by the four FSR piezo resistive force sensors that are on the LARM Hand.

5. The proposed testing procedure

The built test rig is used to perform a set of experimental tests. For each test the LARM hand is set to start at open position of the three fingers, after about 5 seconds the LARM hand starts a phase with closing operation of all fingers. This phase ends with the grasping of the object. As soon as a contact is established between the object and fingers, the force sensors translate the grasping force into a voltage signal. The last phase consists of the opening of all fingers. Figure 5 shows a photo sequence of the testing phases where Fig.5 a) is the starting phase with fingers fully open;Fig.5 b) is showing the closing phase; Fig.5c) shows the phase in which fingers are in contact with the object.

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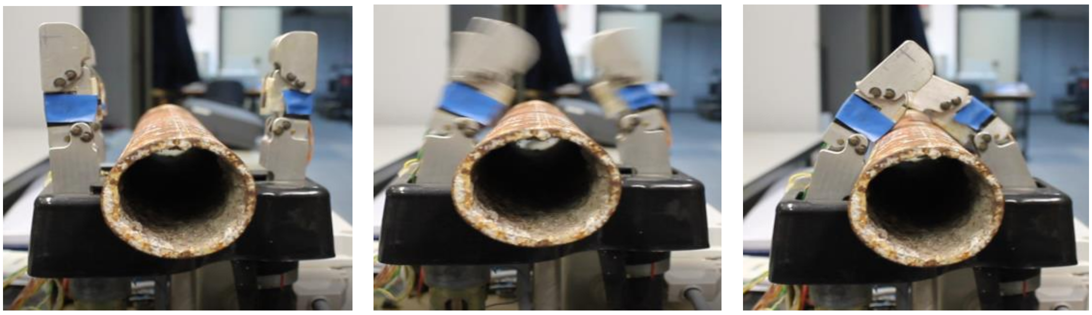
A first set of experimental tests can be defined as vulnerability tests. They are aimed at identifying the vulnerability curve as reported in Fig.6. In particular, the vulnerability curve reports the level of voltage supply conditions that are critical for the operation of LARM Hand. Namely, the vulnerability curve in Fig.6 identifies a set of voltage supply conditions in which the LARM hand is not able to run properly due to a voltage dip.

It is worth noting the vulnerability depends on the combination of duration of voltage dip and the residual voltage %. For example, a voltage dip of 250 ms will prevent the successful operation of LARM hand if the residual voltage is less than 10 %. But, a voltage dip of 250 ms will not produce any effect on the operation of LARM Hand if the residual voltage is higher than 10%. Similarly, a voltage dip of 300 ms will prevent the successful operation of LARM hand if the residual voltage is less than 38 %. But, a voltage dip of 250 ms will not produce any effect on the operation of LARM Hand if the residual voltage is higher than 38%. In other words: any Voltage Dip, whose characteristics (residual voltage % and duration in ms) are below the vulnerability curve is a K.O. for the system; otherwise any Voltage Dips, whose characteristics are below the vulnerability curve is a O.K for the system. It is to note that there is a region close to the vulnerability curve where the LARM hand will be running but a degradation of performance can be expected.



a) b) c)

Figure 5. A sequence of the operation phases of LARM Hand during testing: a) starting phase with fingers fully open; b) closing phase; c) fingers in contact with the object.

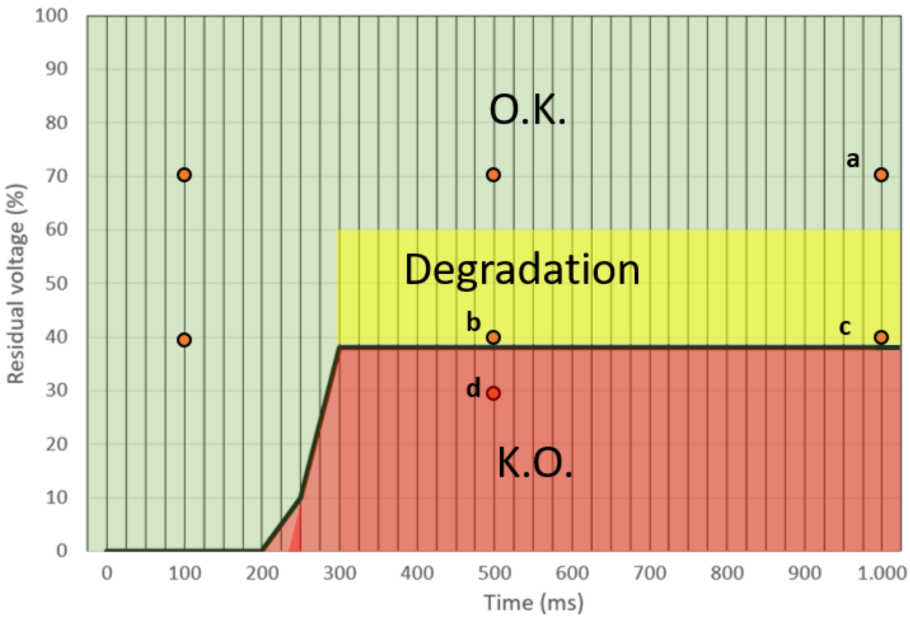


Figure 6. Experimental results in terms of a vulnerability curve for the whole test rig.

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After the above mentioned vulnerability tests, specific tests have been carried out with LARM hand by considering operation conditions being close to the vulnerability curve. The following aspects have been considered as performance parameters for the behavior of LARM Hand during voltage dips:

1- Absorbed current by LARM hand;

2- Tension output from the force sensor.

The tests that have been carried out can be divided into two main cases:

A: Normal condition; The LARM hand is supplied by the nominal sinusoidal voltage without disturbances;

B: Voltage Dip condition; The LARM hand is supplied by a sinusoidal voltage with voltage dips.

The type A case has been investigate to obtain the nominal performance of the LARM hand in order to have a reference nominal output data. The type B cases aims to evaluate the effect of voltage dips on the grasping performance of LARM Hand. In particular, type B cases have been investigated by considering the voltage dips cases, which are reported in Table 2. Results of type A and type B cases is reported in the following section.

Table 2. List of value of the voltages dip used in test.

Residual voltage %	Voltage dip duration (ms)	Test Case
70%	100	a
70%	500	b
70%	1000	c
40%	100	d
40%	500	e
40%	1000	f
30%	500	h

6. The obtained testing results

A first set of experimental results refers to the nominal performance of LARM hand as defined in the type A testing case in the previous section. In particular, it has been possible to collect the current absorbed by LARM Hand in nominal conditions as reported in the plot of Fig.7. Moreover, it has been obtained the output grasping force as measured by the force sensors on each finger of LARM hand in nominal conditions as shown in Fig.8.

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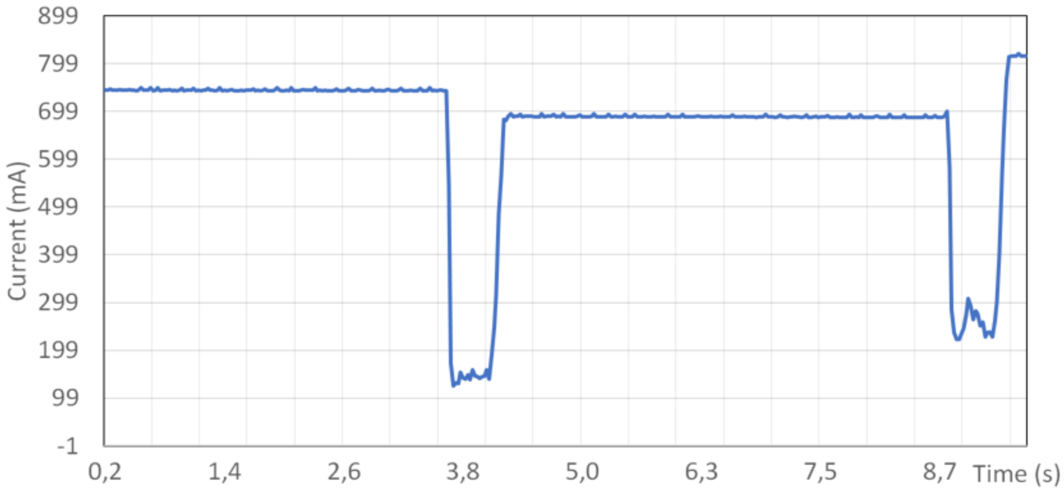

Figure 7. Absorbed current by LARM hand in nominal conditions.

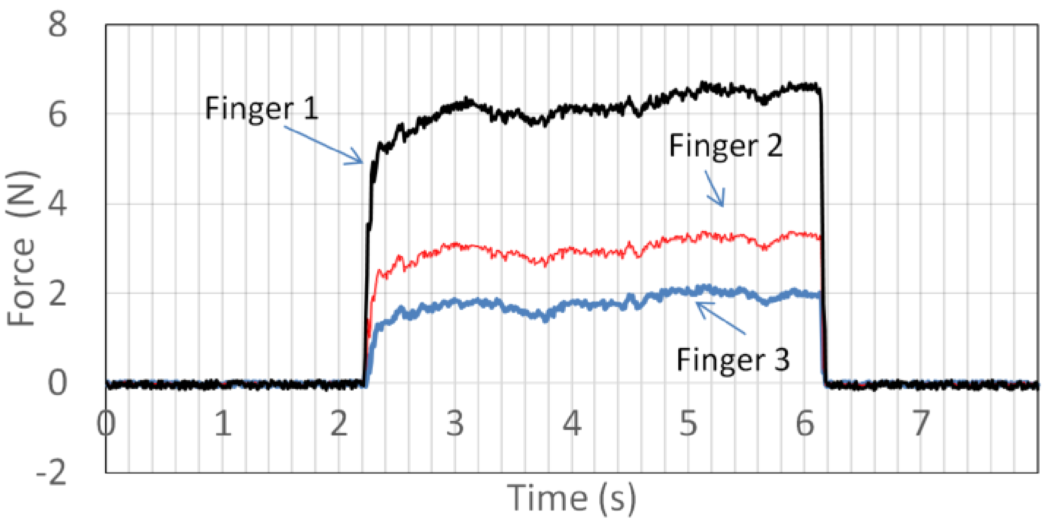

Figure 8. Measured grasping forces in nominal conditions.

Looking at Fig.7 it is possible to observe that in the first line segment the current value absorbed from the system has a average value of 750 mA. The current negative peak occurs in relation with the closing operation. This operation ends with a stabilized current value (660 mA). From the collected data the closing operation lasts for 531 ms. Moreover, Fig.8 shows that the measured grasping forces are all zero until the finger touch the object during the grasping. Then, the grasping force quickly grows until a firm grasp is achieved. At this time oscillations of the grasping force are measured due to small motions of the object as well as due to small changes in the contact point between the object and the sensors as well as small joint clearances on LARM Hand. Additionally, Fig.8 shows that the measured grasping forces on finger 2 and finger 3 are similar while the grasping force on finger 1 is nearly twice as much as finger 2 or finger 3. This is due to the design of LARM hand where finger 1 is placed opposite to both finger 2 and finger 3 so that it needs to apply twice as much force to balance the combined forces due to finger 3 and finger 3.

The following set of experiments refer to cases a, b, and c in Table 2 where voltages dips with residual tension of 70% have been considered. For these cases, any duration of the voltage dip did

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not generate an appreciable variation on the grasping performance of LARM Hand. Given the similar performance of cases a, b, and c in Table 2, only case c is herewith reported. This case, refers to a voltage dip with residual voltage of 70% and duration of 1000 ms. The measured plots for this case are reported in Figs.9 and 10. In particular, Fig.9 shows a comparison of the current absorbed by LARM Hand in nominal conditions and during a voltage dip of 70% and duration of 1000 ms. Fig.10 shows a comparison of one of the measured grasping forces by LARM Hand in nominal conditions and during a voltage dip of 70% and duration of 1000 ms.

The tests with voltage dip with residual tension of 40% and duration of 100 ms (case d in Table 2) have not shown any significant difference as compared with cases a, b, and c. Therefore, the related plots have not been reported in this paper.

The next considered case refers to a voltage dip with residual tension of 40% and duration of 500 ms (case e in Table 2). In Fig.11 it is possible to see the effect, that this type of voltage dip has on the current absorbed by the LARM Hand. This result is even more clear in the zoomed view that is shown in Fig.12 where it is shown the finger closing operation phase. In particular, it is possible to identify in this plot a heavy ripple current. This ripple causes a significant degradation of the grasping performance introducing a relevant delay in achieving the grasping. The produced delay is longer than the duration of the voltage dip as the system takes some time to recover from the voltage dip and go back to nominal operation conditions.. The plot of the grasping force that is reported in Fig.13 shows clearly the effect of the measured current. In fact, the comparison between the measured forces with voltage dip and in nominal conditions shows a very significant change of the grasping force in terms of a step in the grasping force that significantly affects the achievement of a firm grasp.

The first contact between the finger and the grasped object have a similar value of grasping force, but after the voltage dip ends the system starts to get more current and this causes a grasping force increase on the object with the need of achieving a new grasping equilibrium condition and a higher risk of losing the firm grasp of the object.

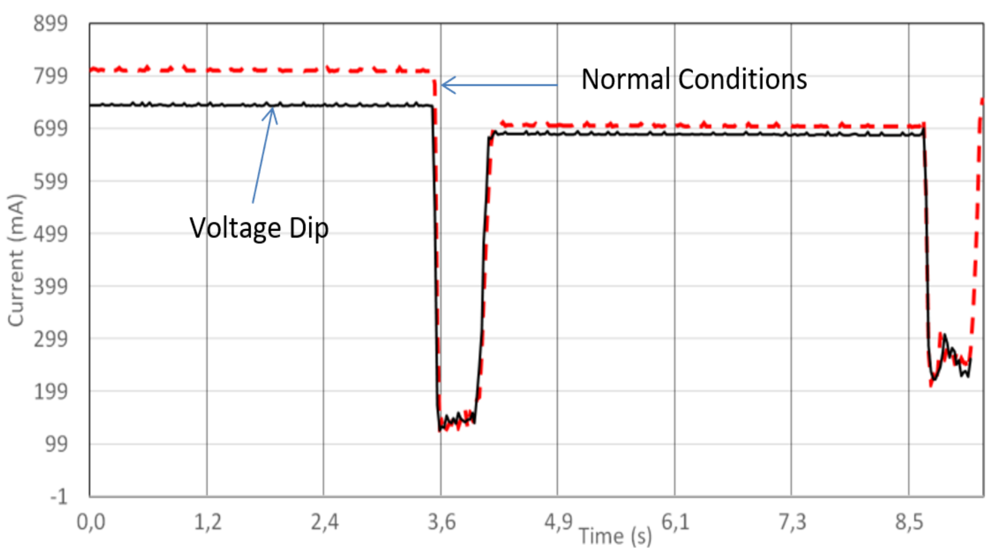

Figure 9. Measured absorbed current with a voltage dip 70% duration 1000 ms (case c in Table 2).

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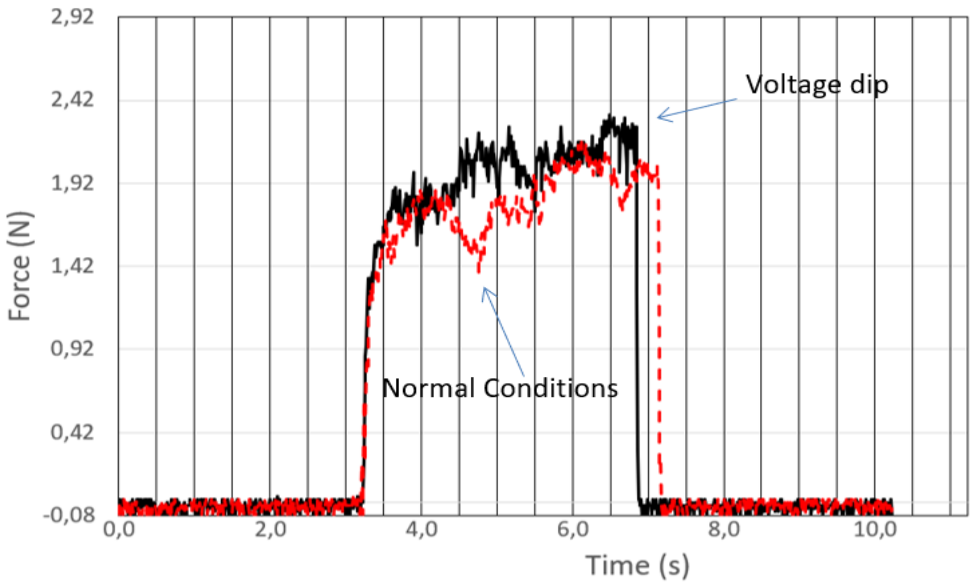

Figure 10. Comparison of the grasping force in normal conditions and voltage dip conditions 70% duration 1000ms (case c in Table 2).

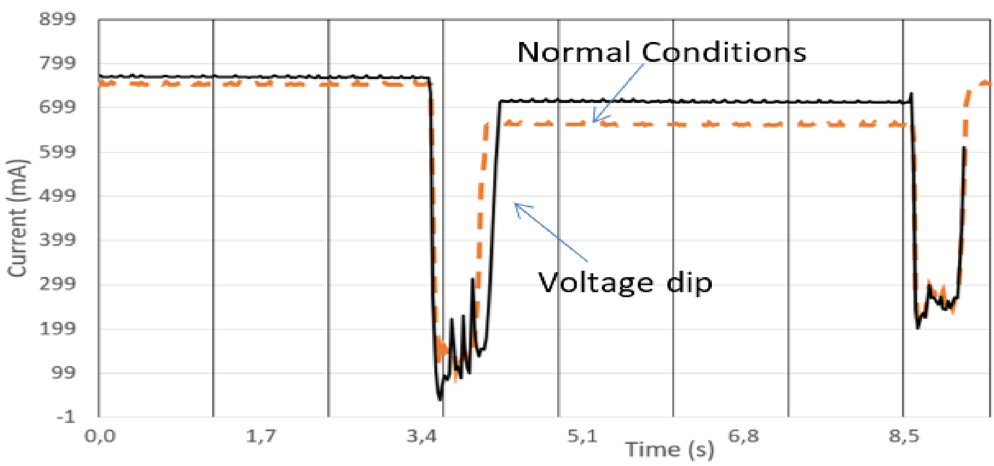

Figure 11. Measured absorbed current with a voltage dip 40% duration 500 ms (case e in Table 2).

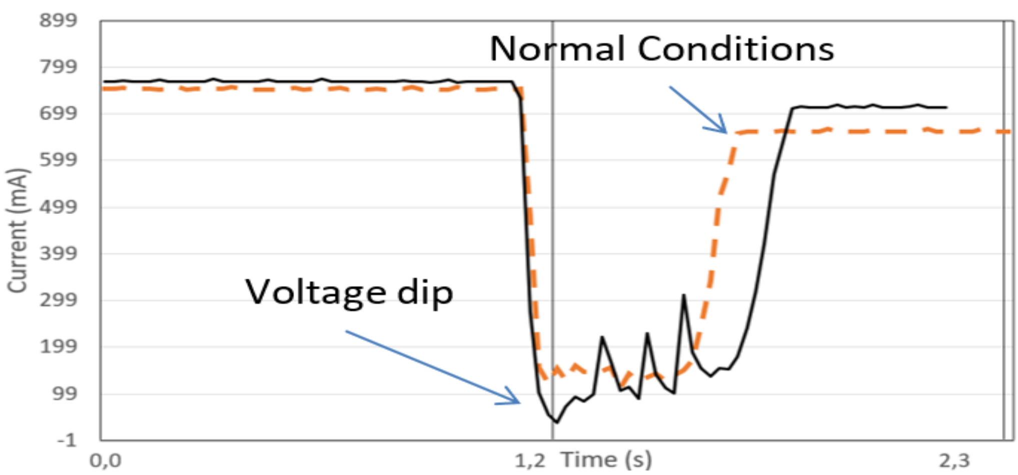

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Figure 12. A zoomed view of the absorbed current with a voltage dip 40% duration 500 ms (case e in Table 2) during the finger closing operation.

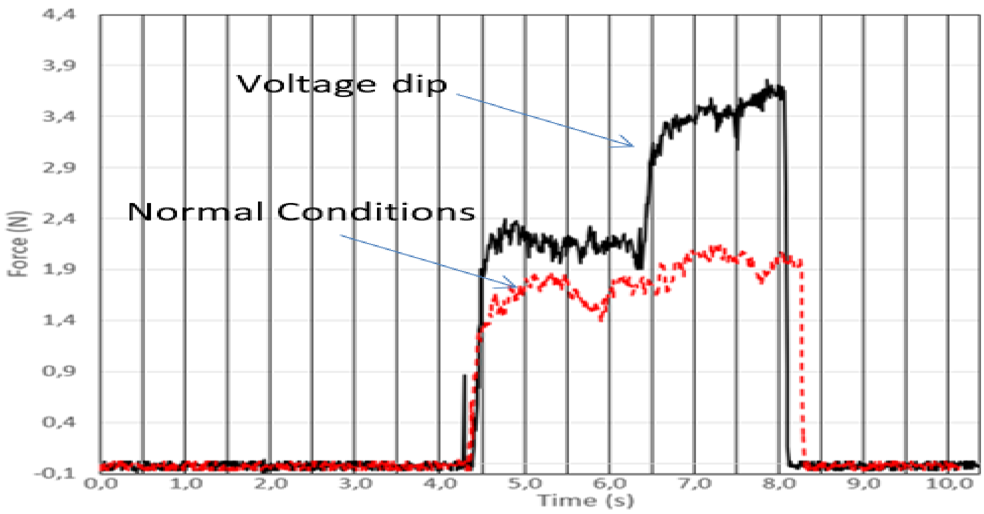

Figure 13. Comparison of the grasping force in normal conditions and voltage dip conditions 70% duration 1000ms (case e in Table 2).

The next considered case refers to a voltage dip with residual tension of 40% and duration of 1000 ms (case f in Table 2). In Figs.14 it is possible to see the effect, that this type of voltage dip has on the current absorbed by the LARM Hand, which is similar to case e in Table 2. Fig.15 shows a zoomed view that is shown in Fig.14 by referring to the finger closing operation phase. In this plot it there is a significant current ripple causing a significant degradation of the grasping performance and introducing a relevant delay in achieving the grasping. The produced delay is significantly longer than the duration of the voltage dip as the system takes some time to recover from the voltage dip and go back to nominal operation conditions. The plot of the grasping force that is reported in Fig.16 shows clearly the effect of the measured current. In fact, the comparison between the measured forces with voltage dip and in nominal conditions shows a very significant change of the grasping force in terms of a step and an about 140% delay in the grasping force. This effect significantly affects the achievement of a firm grasp but this is more smooth than the previously analysed case e of Table 2.

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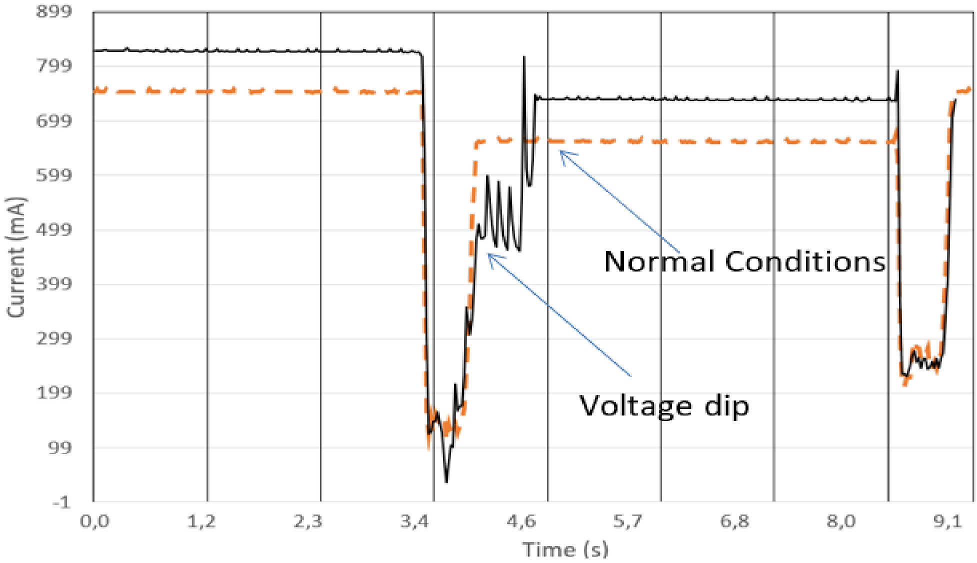

Figure 14. Measured absorbed current with a voltage dip 40% duration 1000 ms (case f in Table 2).

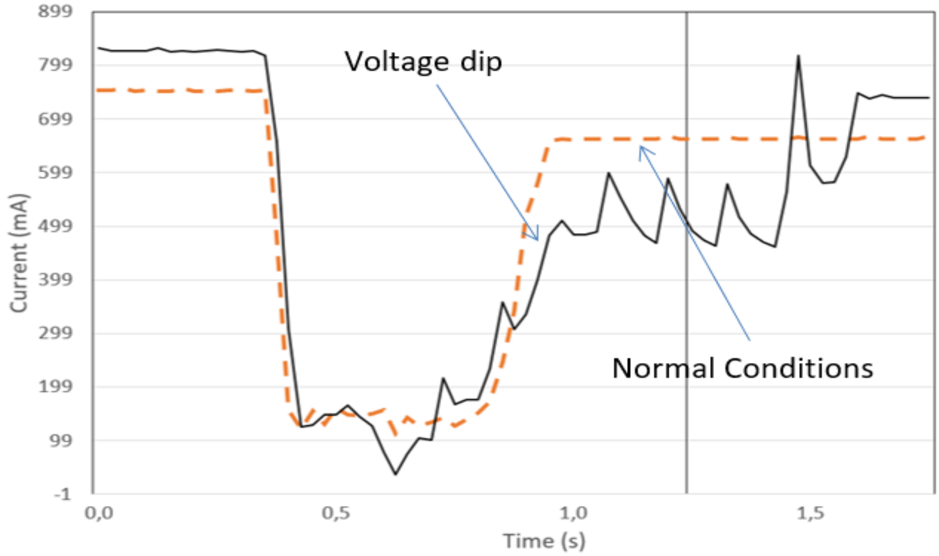

Figure 15. A zoomed view of the absorbed current with a voltage dip 40% duration 1000 ms (case f in Table 2) during the finger closing operation.

In the last case the voltage dip has such characteristics to fall fully below the vulnerability curve shown in Fig.6. This is the most heavy voltage dip in term of residual voltage, which has experimentally tested with residual voltage of 30% and duration 500 ms (case h in Table 2). The measured absorbed currents for this case are shown in Fig.17. This plot show the current absorbed by the LARM Hand is drastically modified as compared with the nominal case. The reason is that this voltage dip causes the restating of the system and the dropping of the grasped object with a complete manipulation failure.

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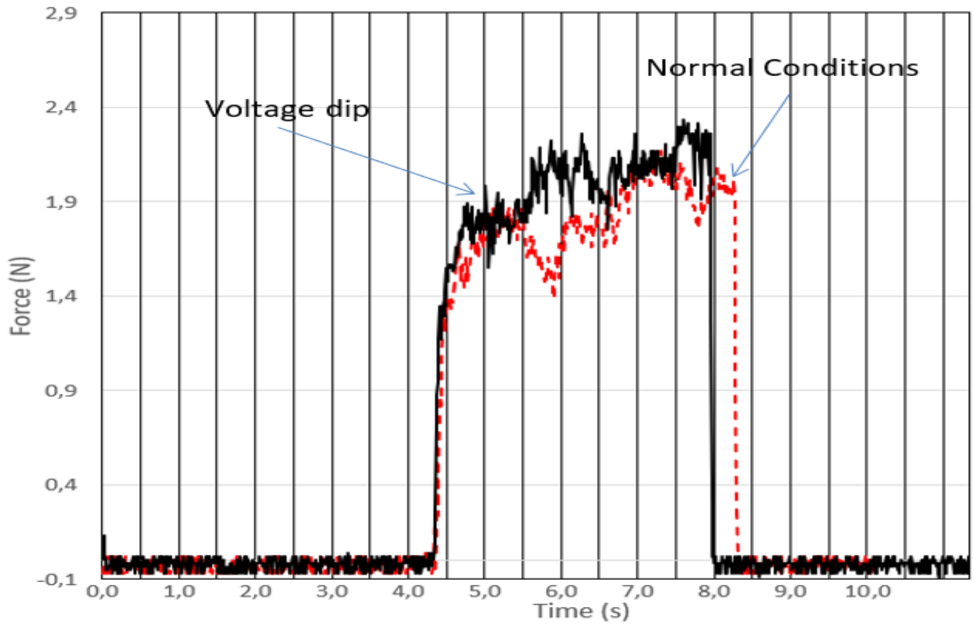

Figure 16. Comparison of the grasping force in normal conditions and voltage dip conditions 70% duration 1000ms (case f in Table 2).

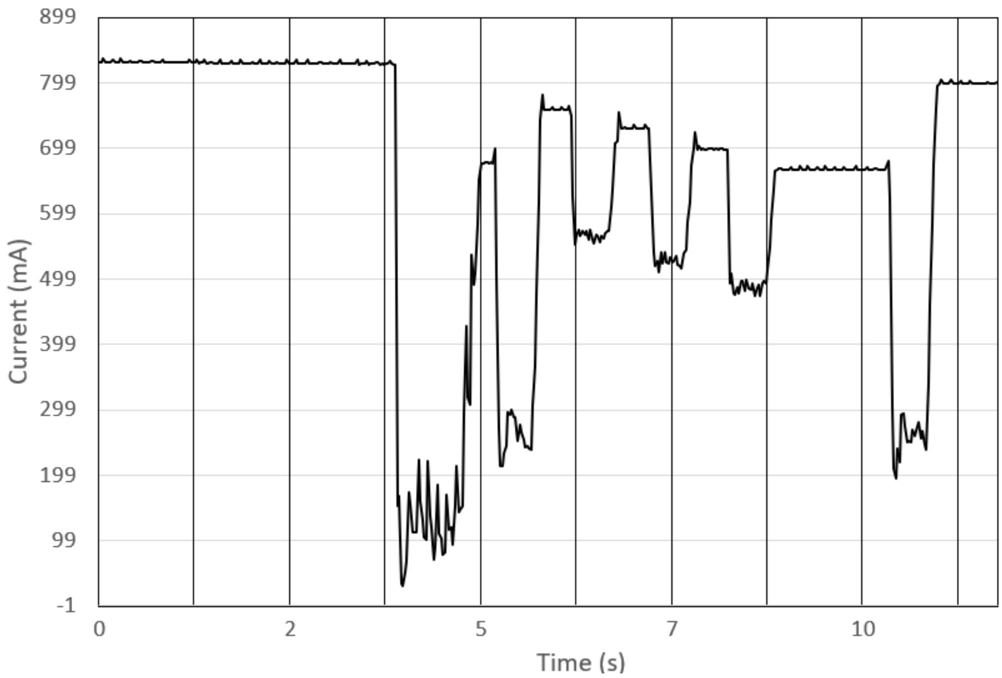

Figure 17. Measured absorbed current with a voltage dip conditions 30% duration 500ms (case h in Table 2); in this case, the LARM Hand fully turns off and restarts after the voltage dip.

Results of the experimental tests prove the significant influence of voltage dips on the grasping performance. In particular, tests have identified three main cases:

- voltage dips being above the vulnerability curve, Fig.6, (residual tension between 90% and 70% of the nominal value and duration under 500 ms); They do not generate any significant degradation of the performance.

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- voltage dips below the vulnerability curve, Fig.6, (residual tension below 40% of the nominal value and duration above 400 ms); They generate a quite significant performance degradation with a temporary complete system shut down. This case is the most undesired one as the grasping/manipulation process is stopped with potential economic implications in an industrial production as well as potential safety implications if the grasping is performed during human-robot collaborative tasks.
- Voltage dips being close to the vulnerability curve shown in Fig.6, (cases between the previous ones); In these cases there is a progressive degradation of performances. The most evident effect is current ripple and a delay in current supply that is amplified in terms of evident delays and steps in the grasping forces that significantly affect the firm grasping as well as that can produce damages on grasped objects due to unexpected overloadings.
- With voltage dip with 40% of residual voltage and duration of 500 ms cause a delay of the closing operation, wich goes from the initial 531 ms in normal conditions to 700 ms, the closing time increasing of 40%. Even the absorbed current is affected by a big variation the maximum difference from the one in normal condition and the one in presence of voltage dip is 500 maA. Regarding the grasp force (Fig.6.6) the step variation can cause, where the object to grasp is very fragile, it's break.

6. Conclusions

This paper addresses the operation of a cable-driven parallel manipulator for rehabilitation tasks. A specific strategy has been proposed to manage cable failures. Namely, once a cable failure is detected, a real-time computation identifies a feasible set of cable tensions, which generates a breaking force that prevents undesired motions of the end-effector. A computation algorithm has been implemented and simulations have been carried out to confirm the effectiveness of the proposed strategy in case of cable failure.

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